THE
ENGLISH ELECTRIC
JOURNAL

VOLUME FOURTEEN • NUMBER FIVE • MARCH 1956

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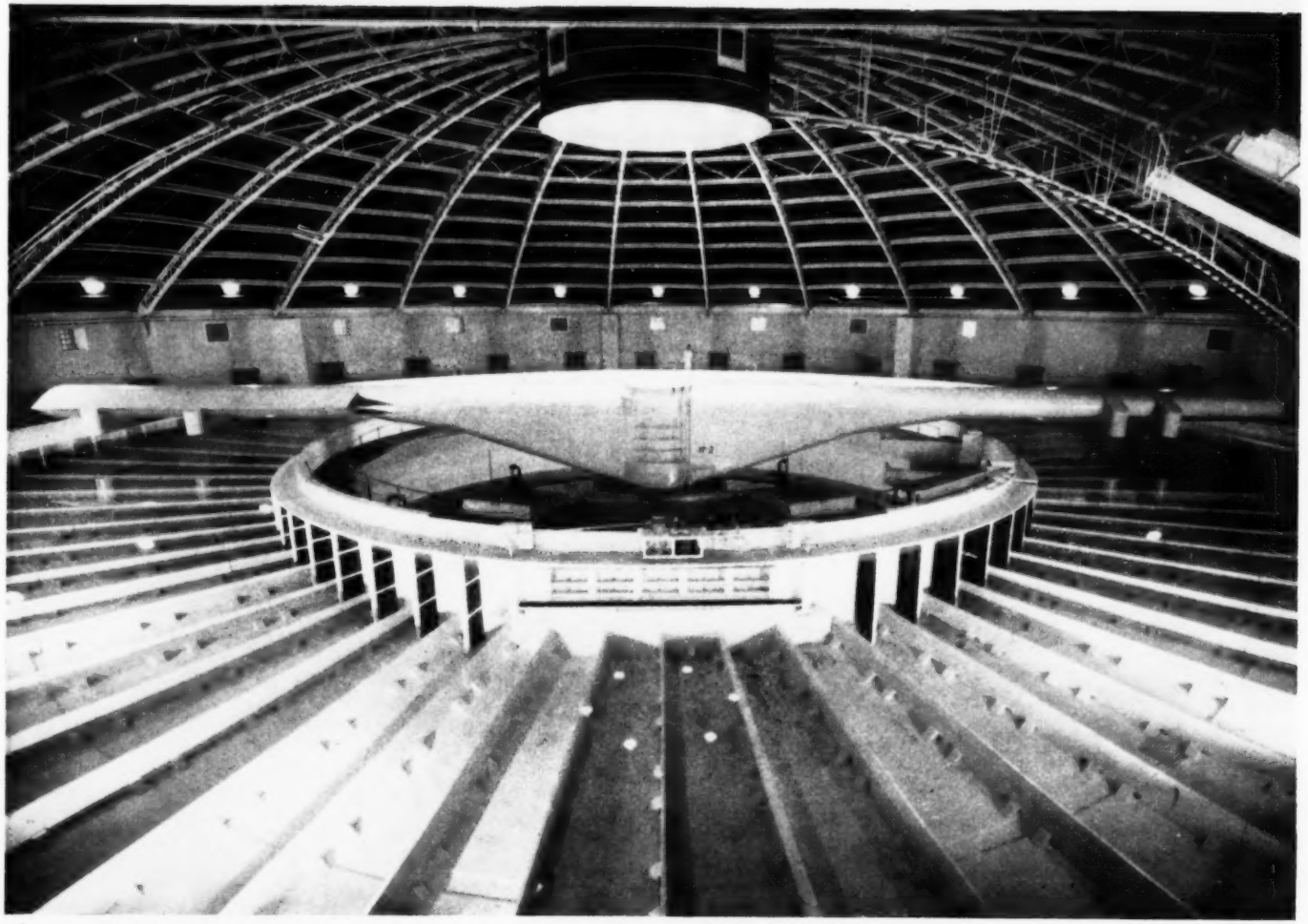


The rotating beam equipment for testing underwater missiles in the Admiralty Research Laboratories at Bushy Park

Speed Control of Rotating Beam Equipment in the Admiralty Research Laboratories at Bushy Park

By A. P. BAINES, Special Engineering Section, and B. W. McLAUGHLIN, B.Sc. (Eng.), Control and Electronics Department.

THE TESTING of underwater missiles in the Admiralty Research Laboratories at Bushy Park has required the construction of several novel equipments. Two such equipments for the observation of the effects of drag, cavitation and the hydrodynamic forces affecting the stability of missiles are a 30-inch Water Tunnel and a Rotating Beam.

The water tunnel consists of a closed circuit in which water is circulated past a stationary model

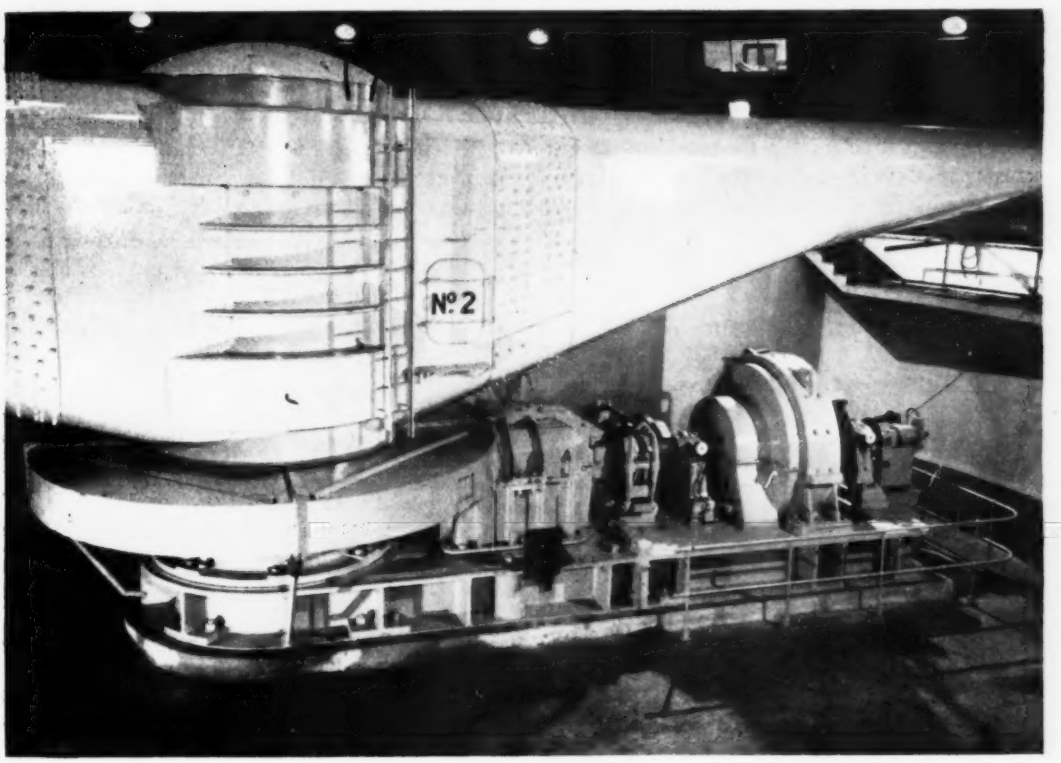


Fig. 1.—The 1510 h.p. d.c. motor driving the rotating beam, with gearbox, holding brake and tacho-generators

by an axial flow pump with a variable-pitch Kaplan runner. The rotating beam on the other hand consists of an open water channel with a beam pivoted on a central island. Models attached to the end of the beam can be submerged in the channel and driven round by rotating the beam about its centre. With both these equipments, the speed holding of the driven elements is of utmost importance, each requiring the use of a closed loop control system.

Due to the difficulties involved in accurately assessing effects on missiles from data obtained from small models, the equipments have been designed not only to test large models but also smaller types of full size missiles. With the application of closed loop control to such systems, the large mechanical inertias involved are of utmost importance.

Since the effects of inertia are more pronounced with the rotating beam equipment, it is this equipment which is described in greater detail here. The method of control and the analysis used for the water tunnel are similar to those for the rotating beam.

The main contractors for the complete equipments were Costain—John Brown Limited, and The English Electric Company supplied the electrical installation for driving and controlling both the rotating beam and water tunnel equipment.

The Rotating Beam Equipment

The rotating beam weighing approximately 60 tons and having an overall length of 122 ft is driven through a gearbox by a horizontal shaft forced-ventilated d.c. motor rated for an output of 1,510 h.p. 750 r.p.m. at 600 volts (Fig. 1). Models may be supported at radii of 45, 50 and 55 ft, the gearbox ratio being arranged to give a top speed of 150 ft per sec to a model supported at 50 ft radius. An electrically operated holding brake is positioned between the motor and gearbox, and at the non-driving end an indicating tacho-generator, centrifugal overspeed device and a high frequency tacho-generator are driven through an auxiliary gearbox.

The beam motor is connected in a Ward-Leonard arrangement to a generator housed in a motor room adjacent to the annular tank. The generator set (Fig. 2) consists of the main generator, synchronous driving motor and three exciters. Two of these exciters have constant voltage outputs to supply excitation for the synchronous motor, beam motor and contactors used in the control scheme. The third exciter is used as a variable voltage machine and is connected to the generator field.

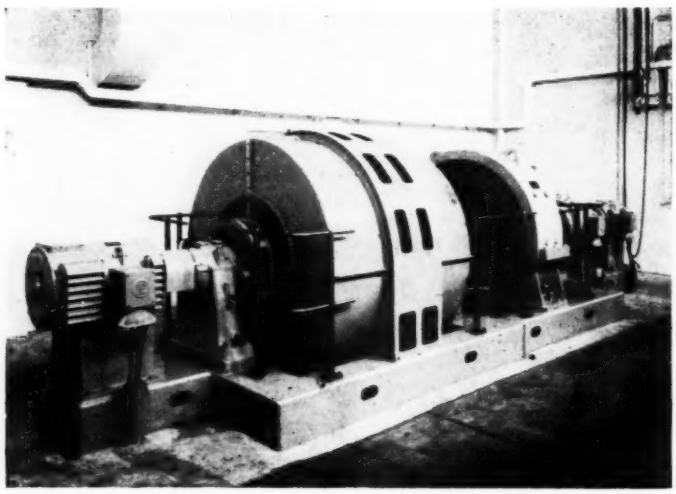


Fig. 2.—Motor-generator set for beam motor

Also housed in the motor room is a solenoid operated d.c. circuit-breaker and a.c. driving motor starting reactor, together with cubicles containing electronic control amplifiers, control relays and contactors. With the generator set running, complete control of the rotating beam is carried out from a control room (Fig. 3) overlooking the annular tank and beam.

Control of Electrical Drive

Manual Control

The system used for manual and automatic control is shown in Fig. 4. With the generator exciter field switch in position 'A' for manual control, the generator exciter field is supplied from a motorised potentiometer connected across a

constant voltage supply. The potentiometer motor is controlled by a switch on the control desk, its speed being set so that safe values of armature current cannot be exceeded on acceleration or deceleration of the beam. On stopping the beam, the generator volts are reduced to a low value by running down the motorised potentiometer, the stored energy in the beam being regenerated to the supply. On reaching a sufficiently low generator voltage an armature voltage relay drops out, allowing the d.c. breaker to be tripped and the mechanical brake to be applied to bring the beam to rest, when the operator depresses a stop button.

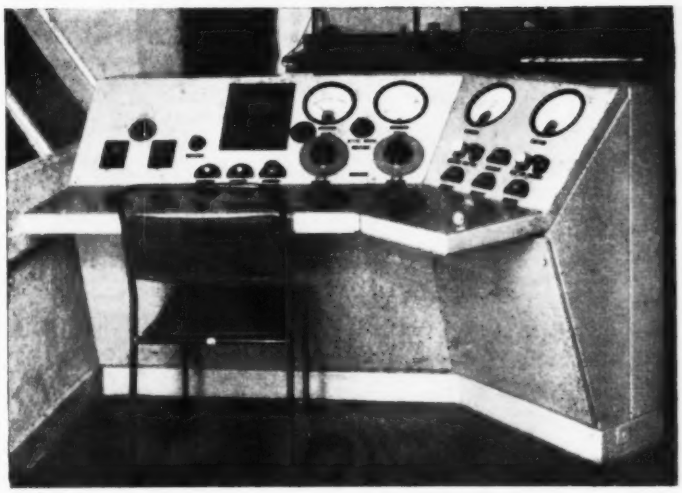


Fig. 3.—Control desk for rotating beam

Push buttons are provided at strategic positions for stopping the beam under emergency conditions. Any one of these will initiate the automatic run down of the control potentiometer. On reaching a low value of speed, the d.c. breaker is automatically tripped and the mechanical brake is applied, the whole sequence taking less than 30 seconds from the top speed to rest.

Automatic Control

The automatic control system is of conventional design. With the generator exciter field switch in position B on Fig. 4, the excitation for the generator field exciter is supplied from an electronic amplifier. The input voltage to the amplifier, which now controls the beam motor speed, is derived from the difference between a stabilised reference voltage which represents the desired beam speed, and the output from a tacho-generator which represents the actual beam speed.

In many tests it will be necessary to maintain the beam speed relative to the water, which may itself be moving. Provision has therefore been

1. Constant voltage exciter
2. Generator exciter
3. Synchronous driving motor
4. Generator
5. Beam motor
6. Auxiliary gearbox
7. Tacho-generator
8. Field switch of generator exciter
9. Current limit signal
10. Electronic amplifier
11. Mixing circuit
12. Speed-setting potentiometers for manual control
13. Speed-setting potentiometer for automatic control
14. Stabilised voltage reference
15. To water-velocity measuring device

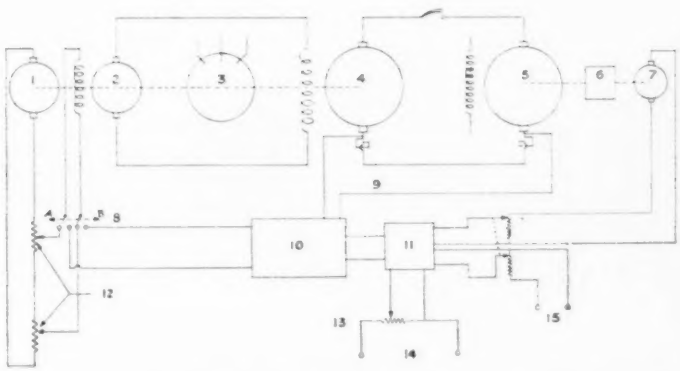


Fig. 4.—Simplified diagram of manual and automatic speed control

made to incorporate a water velocity device designed by scientists of the Admiralty Research Laboratories. The voltage from this device, which is proportional to the beam speed relative to the water, can be made either partly or completely to replace the tacho-generator voltage.

Control System Design

The speed holding requirements for the system are:—

(a) An accuracy of $\pm 0{\cdot}1\%$ of top speed, at all speeds for a load change equivalent to full load on the motor.

(b) An accuracy of $\pm 0{\cdot}1\%$ of the top speed, at all speeds for periods of time of up to 30 minutes.

(c) Control of speed with the above accuracies over a range of 4 : 1. This is equivalent to motor speeds of 187·5 to 750 r.p.m.

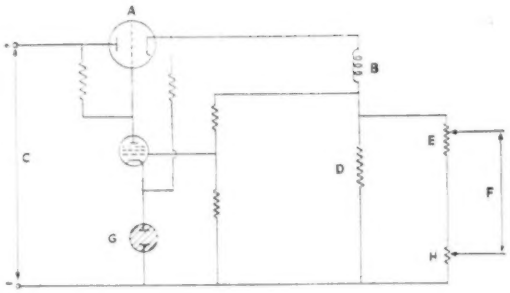
The control system design was based on these requirements and took the form firstly, of selecting a suitable control element; secondly, an estimation of the required system amplification or loop gain in order to maintain accuracy; thirdly, the analysis to determine the stability of the system; and finally, the design of suitable stabilising circuits.

Beam Motor

The rating of the beam motor was based upon the power necessary to accelerate the beam with a water drag load to the full speed of 3 radians/sec in 14 revolutions. The water drag load was taken as having a maximum drag of 4,000 lb at 50 ft radius at a speed of 3 radians/sec.

Tacho-generator and Speed Reference Supply

In such a system as this, random variations in either the reference supply or the tacho-generator output will cause a control signal to be fed to the control amplifier, which as far as the control system is concerned differs in no way from a signal initiated by the operator controlling the system. Similar variations occurring within the control loop although not desirable are not so severe, since the loop gain of the system will reduce their effect. To reduce the random variations in the reference and tacho-generator, special consideration has been given to their design.



A. Series control valve
B. Tacho-generator field
C. D.C. supply
D. High-stability resistance
E. Coarse speed control
F. Reference neon
H. Fine speed control

Fig. 5.—Reference and tacho-generator field supply

The high frequency tacho-generator is an induction machine having both its d.c. excitation winding and a.c. output winding on the stator. This avoids the use of brushgear and the possibility of errors being injected into the system from such a source.

The reference voltage supply to the speed setting potentiometer is obtained across a resistor in series with the high frequency tacho-generator field. The arrangement is shown in Fig. 5.

The supply to the tacho-generator field and the series reference resistor is obtained from a stabilised power supply, using a high stability reference neon. Only the voltage across the reference resistor is maintained constant, and as this is a high stability component it follows that the field current is maintained constant. Further, should the voltage across the reference resistor change by some small amount, this will cause a corresponding change in the tacho-generator field current. With an almost linear tacho-generator characteristic, changes in the reference caused by supply variations are in practice largely cancelled by corresponding changes in the tacho-generator output voltage.

Electronic Amplifier

The error or difference voltage between reference and tacho-generator output, together with suitable

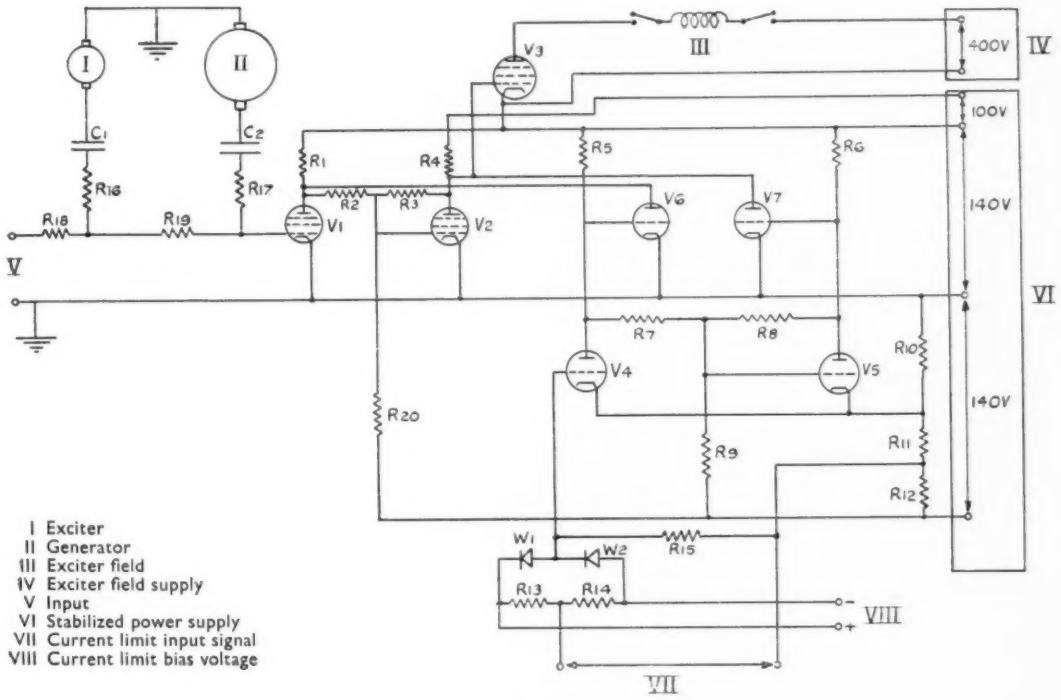


Fig. 6.—Electronic amplifier with associated current-limit amplifier

stabilising voltages, are amplified by a d.c. amplifier having two effective stages of amplification. This amplifier, together with its associated current-limit amplifier, is shown in Fig. 6. V_1 is a high gain stage of amplification and is coupled onto V_2, which inverts the signal without further amplification. V_2 is coupled to the output stage V_3, which controls the generator exciter field.

A d.c. voltage derived from the volt drop across the commutator fields of the motor and generator is used for current limit purposes. This voltage is applied to the grid V_4 via the biassed rectifiers W_1 and W_2. V_4 is coupled to V_5 which inverts the signal without further gain. The circuit is so arranged that with zero current limit signal, the anodes of V_4 and V_5 are at the same potential and are negative to the cathodes of V_6 and V_7. The control grids of V_6 and V_7 being coupled to the anodes of V_4 and V_5 respectively are thus held negative, and V_6 and V_7 cannot pass current. There are two current limit conditions; that due to load in the motor and that due to regeneration when decelerating. Take first the case of current limit due to motor load. On reception of a current limit signal, no voltage will be applied to the grid of V_4 until it exceeds the bias voltage across rectifier W_2. When this occurs, the anode of V_4 drops in potential due to the positive signal on the grid, and the anode potential of V_5 rises. This causes V_7 to conduct and in conducting it reduces the grid potential of V_3, thus restricting the generator exciter field current and in turn limiting the generator current. On regenerative current limit the reverse takes place, this time V_6 conducting and boosting the exciter field.

The bias voltage for rectifiers W_1 and W_2 is controlled from the control desk, thus enabling the current limit setting to be adjusted to give control of the rate of acceleration and deceleration of the beam.

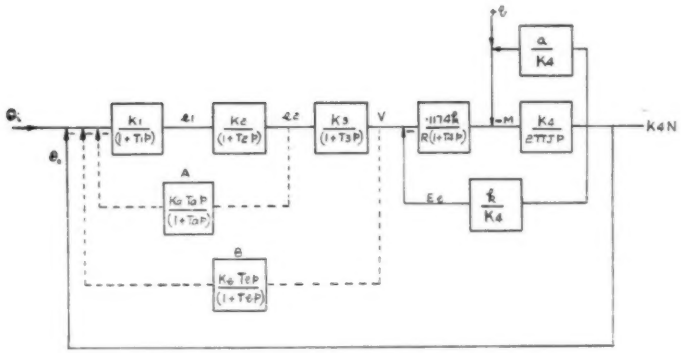


Fig. 7.—Block diagram of speed control system

System Amplification

The action of this type of system is such that the motor speed is proportional to the error or difference voltage between the reference voltage and the voltage supplied by the tacho-generator. The higher the amplification or loop gain of the system, the smaller will be the error voltage. The advantage of a high loop gain is apparent when the effect is considered of applying an external disturbance to the system tending to alter the motor speed. Even a comparatively small change in the error voltage caused by a small change in motor speed will give rise to a large correcting action to oppose the external disturbance. Thus the larger the loop gain, the smaller will be the motor speed variation required to give rise to the necessary correcting action.

By considering the effects on the system of variation of supply voltage and frequency and ambient temperature, as well as the effect of a load disturbance equivalent to full load on the motor, an estimation was made of the required loop gain, being of the order of 100. However, it will be appreciated that in maintaining the loop gain above this value under all running conditions, the characteristics of the components used in the system will cause the loop gain to vary. In practice, the loop gain is at a maximum of 215 at half full speed, when the corresponding gain is 100 at top speed, the reduction being due to generator field saturation at the higher speed.

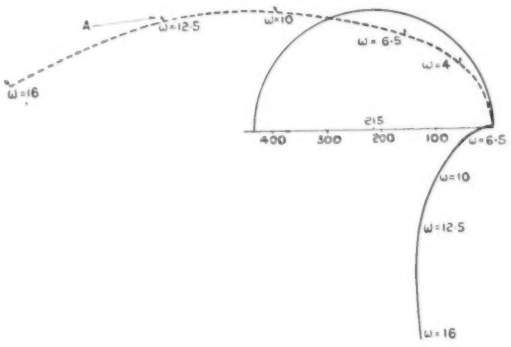
Analysis

Reasons for Analysis

The required loop gain for the system, ascertained for steady state conditions, takes no account of the effect of suddenly applying a disturbance to the system. With the mechanical and electrical inertias present in such a system, the loop gain chosen may not only cause the system to exhibit an unsuitable response to such a disturbance, but may, if large, cause the system to be completely unstable. The analysis which follows was made to determine the stability of the system and to design stabilising circuits, which not only prevent instability but impart to the system the best response to any applied disturbance.

Block Diagram

The block diagram representation of the system is shown in Fig. 7. Each block represents the transfer function, or relationship between output and input of each element in the speed control. Such a diagram is built up from the system equations which are given under the next heading.



A. Effect of water load 4,000 lb 50 ft radius at 3 radians per second

Fig. 8.—Inverse Nyquist diagram showing the effect of stabilizing feeds-back and water load

The following symbols are used.

θi = Reference voltage
θ_o = Tacho-generator output volts
e_1 = Electronic amplifier output volts
e_2 = Exciter output volts
V = Generator output volts
E_b = Motor back e.m.f.
I = Generator and motor armature current
T_1 = Time constant of electronic amplifier
T_2 = ,, ,, ,, exciter field circuit
T_3 = ,, ,, ,, generator field circuit
T_4 = ,, ,, ,, generator and motor armature circuit
k = Motor constant in volts/r.p.s.
K_4 = Tacho-generator constant, $\frac{\text{tacho volts}}{\text{motor r.p.s.}}$
R = Generator and motor circuit resistance
J = Motor armature and load inertia
N = Motor speed in r.p.s.
p = Differential operator
M = Total load torque
a = Load torque in lb ft/r.p.s.
b = Constant water torque as defined by equation (1)

SYSTEM EQUATIONS

Water load $M = aN - b$ . . . . (1)

The assumption here is that at any given speed the water load is linear about that point. It will be shown, however, that the effect of load, though small, has a stabilising effect upon the system, and since the system must be capable of running with no load, it is this condition which must be investigated.

Ward-Leonard set voltage equation

$$V - E_b = IR\,(1 + T_4 p)$$

Torque equation

Electrical torque = load torque + acceleration torque

$$\cdot 1174\, kI = M + 2\pi JpN$$

Generator equation

$$V = \frac{e_2 K_3}{(1 + T_3 p)}$$

Exciter equation

$$e_2 = \frac{e_1 K_2}{(1 + T_2 p)}$$

Electronic amplifier equation

$$e_1 = \frac{E K_1}{(1 + T_1 p)}$$

Difference voltage fed to the electronic amplifier

$$E = \theta_i - \theta_o$$

Tacho-generator equation

$$\theta_o = K_4 N$$

The criterion used to ascertain the stability of the system is to determine if there is any frequency of input quantity which, if applied to the system, would cause the output quantity to be larger in magnitude than the input, and to be reversed in phase due to the system time lags. If there is such

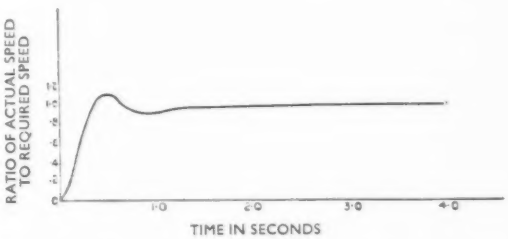


Fig. 9.—Theoretical response of system to a unit step of input

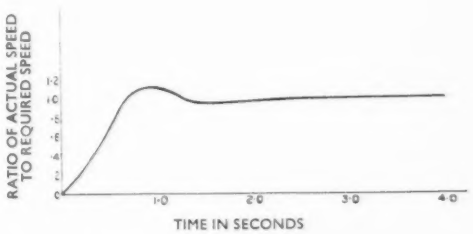


Fig. 10.—Response of rotating beam to a unit ramp input closely approximate to a unit step

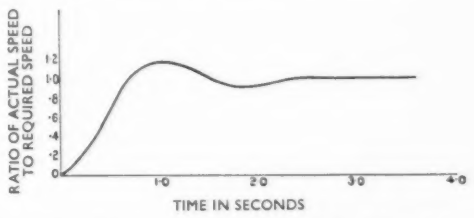


Fig. 11.—Improved response to a unit ramp input closely approximate to a unit step

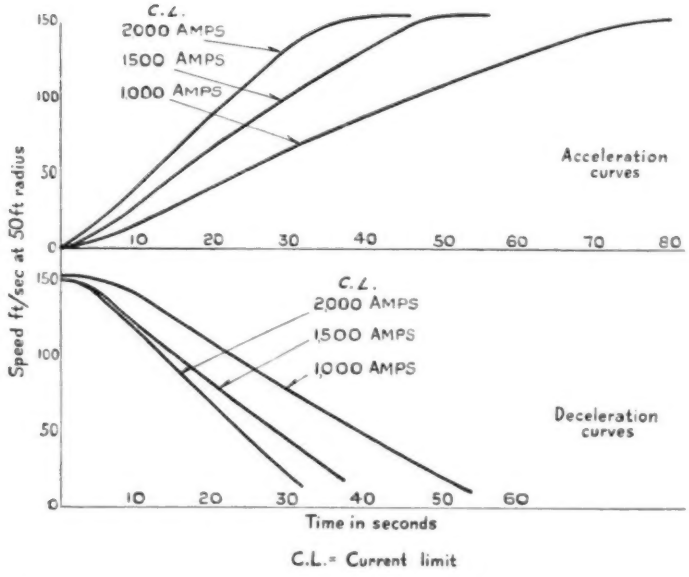


Fig. 12.—Acceleration and deceleration under current limit control

a frequency of input then the system will be unstable.

To apply this criterion, an Inverse Nyquist diagram is plotted, being the locus of the vector $\frac{E}{\theta_o}$ for variations in frequency from zero to infinity.

The expression for $\frac{E}{\theta_o}$ for this system may be shown to be

$$\frac{E}{\theta_o} = \frac{1}{m}\left[(1+T_1p)(1+T_2p)(1+T_3p) + (1+T_1p)(1+T_2p)(1+T_3p)(1+T_4p) \times T_op + Km(1+T_1p)(1+T_2p)(1+T_3p) \times (1+T_4p)\right]$$

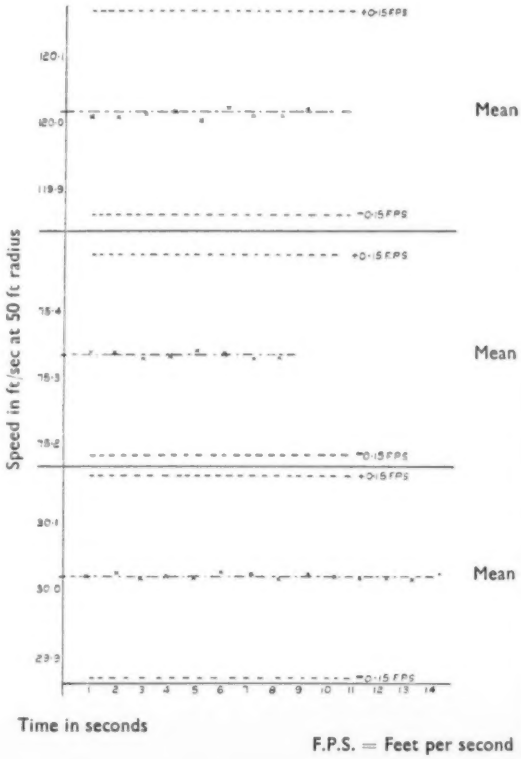
Fig. 13.—Typical short duration speed holding tests on rotating beam

where $T_o = \frac{2\pi JR}{\cdot 1174\, k^2}$ = mechanical time constant

$Km = \frac{aR}{\cdot 1174\, k^2}$ = effect of water load

and $m = \frac{K_1 K_2 K_3 K_4}{k}$ = loop gain.

Due to variations of loop gain and time constants at different speeds, several Inverse Nyquist diagrams were plotted. One such diagram is shown in full line in Fig. 8, this being for the beam unloaded and running at half full speed.



This diagram indicates that for a loop gain in excess of 20, the system will be unstable. Since a loop gain of 215 is required at half speed to maintain the required accuracy, stabilising circuits must be employed to modify the system, not only for the condition shown but under all running conditions. The circuits found to be most suitable are shown on the block diagram as blocks A and B. These have the effect of feeding back to the input of the electronic amplifier, voltages proportional to any transient voltages appearing on the exciter and generator output terminals. The effect upon the Inverse Nyquist diagram is shown in dotted line in Fig. 8.

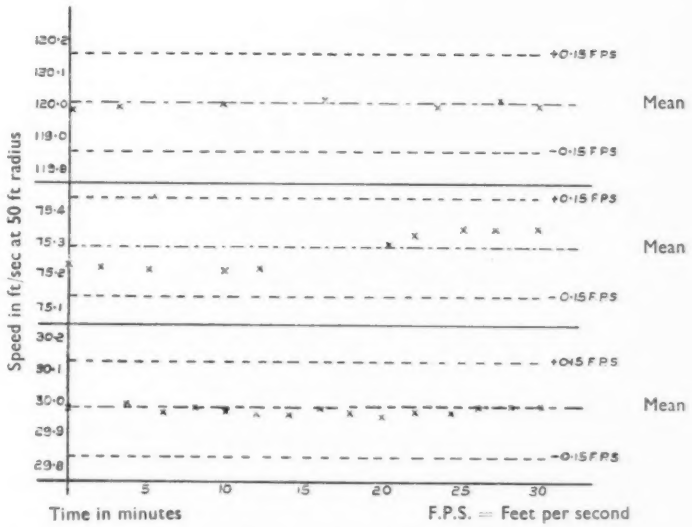


Fig. 14.—*Typical long duration speed holding tests on rotating beam*

To this locus has been added a vector which indicates the effect of loading the beam with a water drag load, its effect being shown to be negligible.

To complete the analytical study of the system, the response to a step of reference voltage was also determined. This is plotted in Fig. 9, showing that for a small change of speed initiated by an operator, provided the accelerating current in the Ward-Leonard loop does not exceed the current limit value, the system will settle within 5% of the required setting in approximately 1 second, finally reaching the desired value in approximately 4 seconds.

Tests During Commissioning

Having fully adjusted the equipment for manual operation, the speed control response for small changes in speed setting was obtained by recording in oscillogram form the output voltage from the speed indicating tacho-generator. Fig. 10 shows a typical response to a ramp input which closely approximated a step input, using the stabilising circuit as determined from the analysis. However, it was found that by adjusting the stabilising circuits, the improved response shown in Fig. 11 was obtained, the long exponential settling time of beam speed having been reduced, giving an improved settling time of approximately 2½ seconds.

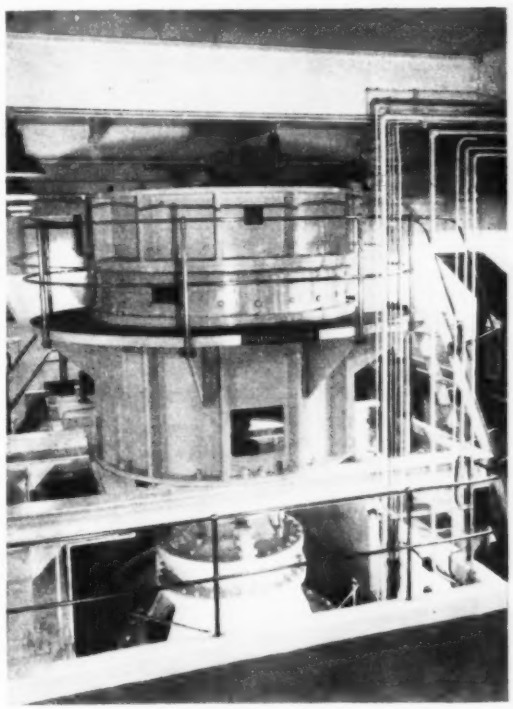


Fig. 15.—*The* 850 *h.p. d.c. motor driving the axial flow pump of the water tunnel*

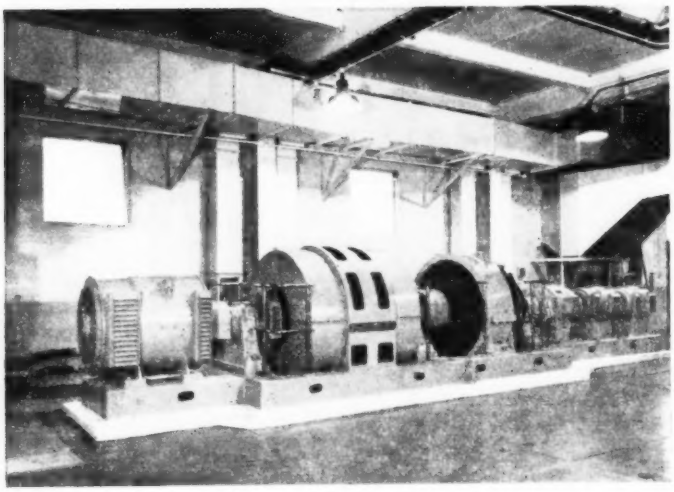


Fig. 16.—Motor-generator set for power supply and control of water tunnel pump motor

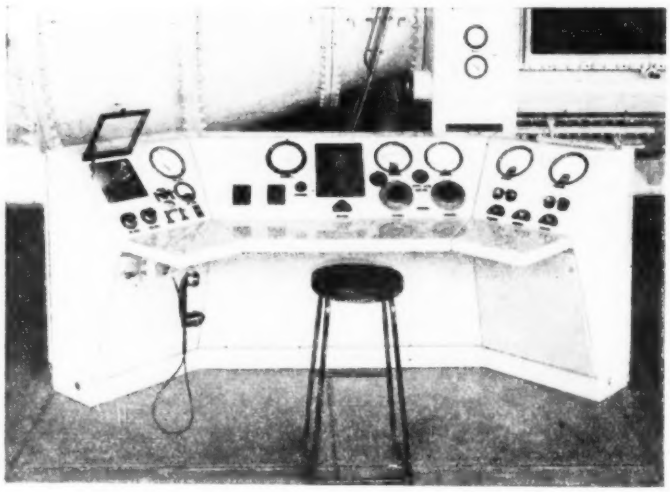


Fig. 17.—Control desk at working section of water tunnel

During this commissioning period, adjustment was made to the current limit circuits which included a stabilising feedback. Test results taken in conjunction with the Ministry of Works and the Admiralty Research Laboratories are given in Figs. 12, 13 and 14, which show typical acceleration and deceleration characteristics of the beam under current limit control, and typical speed holding characteristics both for short periods and for long periods.

Water Tunnel

As mentioned earlier, the method of speed control and the analysis used for the 30-inch water tunnel are similar to those for the rotating beam. From the point of view of the electrical drive, the significant difference between the equipments is in the driving motor. For the water tunnel equipment this motor is a vertically mounted 850 h.p. 220 r.p.m. 450-volt d.c. machine, directly coupled to the axial flow pump (Fig. 15). The pump, motor, associated motor-generator set (Fig. 16) and control amplifier are on the ground floor of the building, and the control desk (Fig. 17) is on the floor above, close to the working section of the tunnel containing the model under test.

Acknowledgments

The electrical equipment described in this article was supplied to the specification of Mr. M. Woolfson, A.M.I.E.E., M.Amer.I.E.E., Senior Engineer, Ministry of Works. The authors acknowledge the help given by Mr. Woolfson and his staff, particularly in providing the speed holding and acceleration curves.

The Napier Investment Foundry

THE NAPIER INVESTMENT FOUNDRY at Park Royal, London, was established in 1948 for the production of turbine blades and other components required for the Napier Company's turbo-blowers and gas-turbine aero engines. Two years later the facilities of the foundry were made available to industry generally, and it is now one of the largest investment foundries in Britain, producing a very wide range of small parts for a variety of engineering industries.

Many manufacturers have found in the investment casting process a solution to some of their small-part production problems. Small intricate components which, by conventional methods, could not be made economically or could not be made in one piece and had to be assembled from several small parts, and parts which had to be redesigned to be produced at all, have often been made quite easily and comparatively cheaply by the investment casting process.

A Complicated Casting

The component selected to illustrate this article, a seal housing, provides a fair example of the way in which increased design freedom can be derived from the use of investment castings, as it was produced by the investment casting process after attempts to make it by conventional methods had proved either technically or economically unsuccessful.

A brief description of the seal housing (Fig. 1) will make some of the production difficulties apparent. The housing body is cylindrical, and from it project two flanges. Each flange projects from the body at a different angle and communicates with a different part of the housing ; the large flange with a channel cast in the housing bore, and the small flange with an opening in the outer surface of the housing. An additional complication from the manufacturing point of view is that both flanges are undercut, the bore of the large flange being butter-bean shaped at the top and lengthening and thinning towards its base.

Fig. 1—The seal housing made by investment casting after unsuccessful attempts by conventional methods

Investment Casting and the Seal Housing

Investment casting is carried out in four main stages : (1) the construction of a metal die of the part to be cast ; (2) the forming of expendable wax patterns from the die ; (3) the construction of refractory moulds from the wax patterns, and (4) the pouring of molten metal into the moulds.

The Napier foundry's technical staff decided that, in the initial stages of the process, the housing should be broken down into five pieces. A wax pattern of each of the five pieces would be made, the patterns assembled, and the seal housing cast in a mould formed from the assembly.

The pipe connection flanges were separated from the body of the housing and each flange was split in half axially. Aluminium models of the halves

Fig. 2—A die and model maker finishing the two halves of the model of the large flange. In the foreground are the top and bottom halves and the three core pieces of the die for the housing body

of each flange were made, and soft metal (tin-bismuth alloy) dies cast from them. A die for the housing body was cut from an aluminium block. Three core pieces had to be made and these were located in the bottom half of the die by set screws (Fig. 2).

Usually dies are cut direct from a metal block only when the shape required is so complicated that die cutting is no more difficult or expensive than making a model and casting a die from it. Model and die making constitutes the 'tooling up' stage of the investment casting process, and the soft metal dies can be used to make thousands of wax patterns.

Making the Wax Pattern

The die making stage completed, production of the castings begins with the making of the expendable wax patterns. The finished dies of the housing body and flanges are injected with molten wax and the resultant wax patterns assembled to form a complete wax replica of the seal housing. One such wax replica is made for every casting required.

An injection-machine operator cleans and assembles the dies, and then places a die on the table of her machine so that the injection nozzle of the machine enters the feed hole in the die. The operator pushes a button and the rest of the injection operation is automatic: the die is clamped in position, the correct quantity of wax at the correct temperature is injected into the die, and the clamp continues to hold the die until the wax is cool enough to be handled. When the clamp releases the die, the operator separates the die halves and removes the wax pattern (Fig. 3).

When all five wax pieces of the housing pattern have been made, they are conveyed to another operator who inspects them and then assembles them into the complete pattern. First, the halves of the flanges are joined. The two pieces of a flange are held together and the edges aligned. A heated spatula, run along the edges, melts the wax on either side of the join so that the edges weld together.

The assembled flanges are now attached to the housing body (Fig. 4). There is a raised lip on the body of the housing where each flange is to be attached, and the flange is held in position on its respective lip and the heated spatula applied to the edge of the flange where it joins the lip. Both the inside and outside edges of the joins are treated in this way.

A wax pattern the exact shape of the desired casting has now been formed. At this stage the dimensional accuracy of the pattern is checked and surface blemishes are corrected. Wax runners are attached to the base of the pattern, the assembly is weighed, and from the weight of wax used in the assembly the weight of casting metal required is ascertained.

Investing

The next three operations, dip-coating, sanding, and investing are carried out in the investment department. Dip-coating, the dipping of the wax

Fig. 3—The die halves are separated, releasing the wax pattern formed by pressure injection

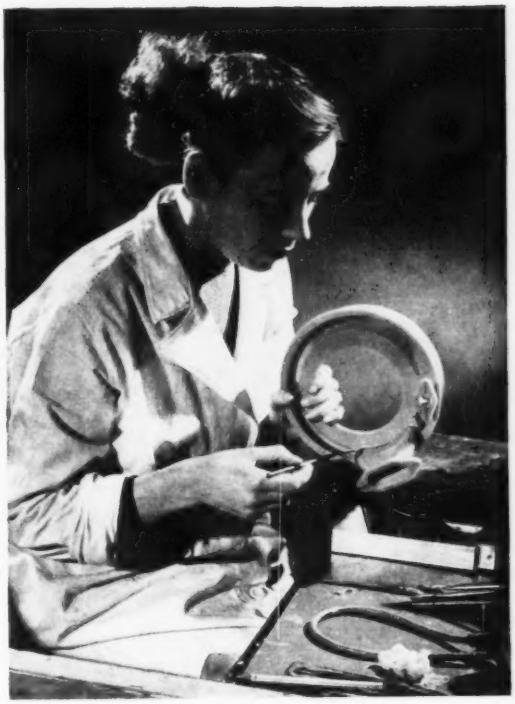
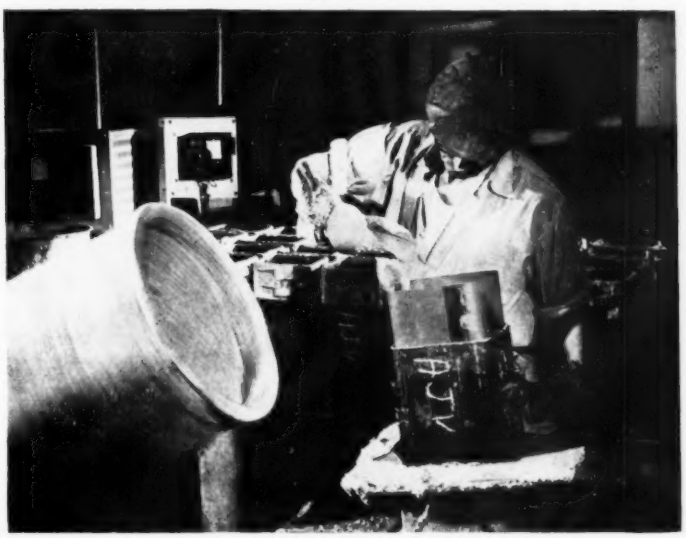


Fig. 4—The large flange being 'welded' to the wax pattern of the housing body with a heated spatula



pattern into a fine refractory solution, ensures that the inside surface of the mould will be smooth and will therefore impart a smooth finish to the casting.

Sand, sprayed over the coated pattern while it is still wet, adheres to the film of solution and will serve as a bond between the fine refractory and the coarser investment.

Fig. 5—Pouring the slurry into the flask, carefully, to avoid damage to the wax assembly

The forming of a mould around the wax pattern is called ' investing ' and the casting will be made from this mould. The coated and sanded pattern is placed on a drilled steel plate so that the funnel-shaped runner on the base of the housing is in the centre of the plate. An open-ended canister, lined with waxed paper, is placed on the steel plate, so ' boxing in ' the pattern ; hot wax is then poured around the base of the canister to seal it to the plate. The assembly of steel plate, canister, and wax pattern, is called a ' flask.'

The flask is stood on a small vibrating table and filled with the investment slurry, which is a coarse refractory solution. As the vibration transmitted from the table releases the air bubbles from the solution the slurry packs closely around the pattern (Fig. 5).

When full the flask is removed to a larger vibrating table where, with other flasks, it remains until all excess fluid in the solution has risen to the surface. The fluid is poured off and the flask is then stored at room temperature to allow the slurry to set.

Pre-heating, Firing and Casting

The hardened mould is next conveyed to the furnace room where the first operation is the melting of the wax pattern from the mould ; this is accomplished in a gas-fired pre-heating oven. The temperature of the pre-heating oven is slightly above the melting point of the wax and, as the mould is passed slowly through the oven, the wax melts and runs out of the mould.

The mould, having in its centre a cavity the shape of the seal housing, lined with fine refractory material, is now hard enough for the canister to be dispensed with, and is ready for firing.

Firing, which is carried out in a tunnel furnace, increases the permeability of the mould to allow the gases given off by the metal during casting to escape. The temperature is progressively higher along the length of the furnace, so that as the mould is conveyed slowly through the tunnel its temperature is raised gradually to about 1,000°C (Fig. 6).

While the mould is being fired in the tunnel furnace, the casting metal is being melted in a small electric-arc furnace (Fig. 7).

When the correct casting temperature, usually in the region of 1,500°C, is reached, the mould is taken from the tunnel furnace and clamped on the top of the arc-furnace, with its runner hole directly over the furnace aperture. Furnace and mould are then inverted and air pressure is applied to the crucible of the furnace to pressure-pour the molten metal into the mould, pressure-pouring ensuring sharp definition in the casting.

Fig. 6—The empty mould begins its journey through the tunnel furnace

The Final Stages

The pouring operation empties the furnace, since it was charged with the exact quantity of metal required to cast one seal housing, and the mould is now detached from the furnace and conveyed to the knock-out shop, the conveyor speed being such that by the time the mould reaches the knock-out shop it is cool enough to be handled.

In the knock-out shop, the

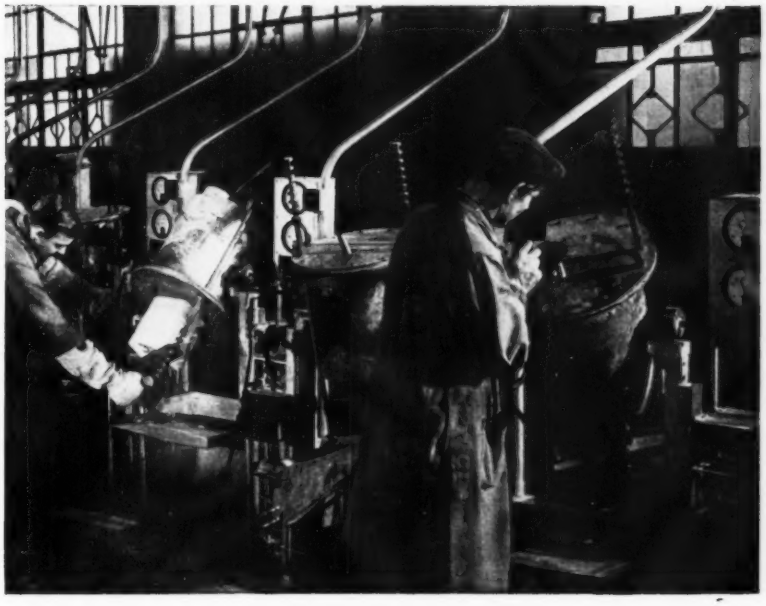


Fig. 7
The billets of casting metal being melted in electric arc furnaces. The furnace with a mould clamped to it is being inverted in the pouring operation. The conveyor behind the furnaces carries the full moulds to the knock-out shop

mould is broken open by pneumatic hammers and the casting extracted (Fig. 8).

Fragments of the fine dip-coat which may adhere to the casting are removed by shot blasting, after which the casting is taken to the cut-off and fettling shop where the runners and flash lines are removed and small surface imperfections ground off.

Production of the casting is now almost complete. After the final machining of certain faces, a visual inspection for casting faults and surface blemishes, and a dimensional accuracy check (Fig. 9), the seal housing will be ready for use.

The Need for Control

The necessity for strict control of the progress of a component through the foundry, from drawing board to finished casting, will be evident. To eliminate delays and bottlenecks, the duration of each operation and the speeds of the conveyors which link the operations are carefully planned. In the firing stage of the process, for instance, the mould takes several hours to pass through the tunnel furnace, and firing must be completed at the same time as the casting metal in the arc-furnace reaches its correct casting temperature. In the knock-out stage, the moulds must be cool enough to be handled when they arrive at the knock-out shop. The conveyor which carries the moulds from the furnaces to the knock-out shop must move quickly enough to keep the furnace-room free of finished moulds, but slowly enough to allow the moulds to cool before reaching the shop. Similar controls ensure the even progress of production at all stages of the process.

Facilities and Services

Every casting produced by the Napier Foundry is subject to close inspection for quality and conformity to requirements. The inspection department uses the most up-to-date equipment, including optical comparators and dual projection machines, and is fully approved by the Aeronautical Inspection Directorate. This inspection equipment is kept at a high level of efficiency by extensive standard room and gauge inspection organisations.

The foundry has access to the modern chemical, physical, metallurgical and radiological laboratories maintained by the Napier Company for the control of quality of materials. As a result of these facilities, the foundry is specially approved for work in D.T.D.666, D.T.D.705, and allied specifications.

An important feature of the foundry is a technical

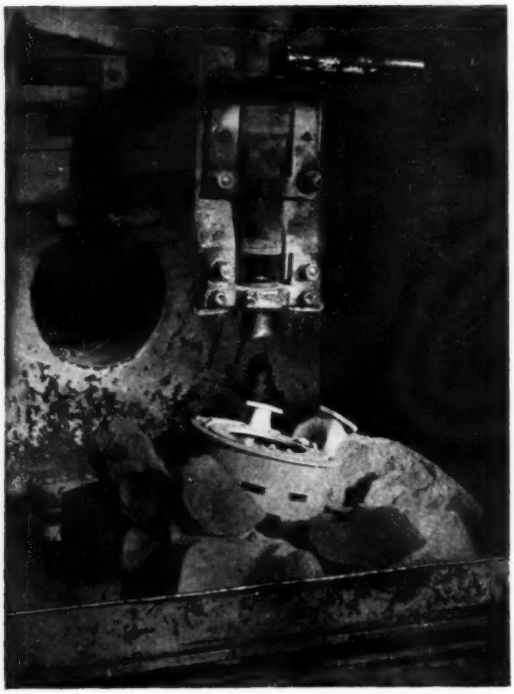


Fig. 8—A pneumatic hammer is used to break open the mould and release the casting

advisory service with a staff having wide experience of investment casting, to advise on the best means of obtaining the casting required and to co-operate in its design and production.

The Economics of Investment Casting

Manufacture of the seal housing by the investment casting process solved a difficult production problem, and allowed the component to be made much nearer to the ideal shape than would have been possible by any other method. Although the solution of such problems is part of the everyday routine of the foundry's technical staff, their main concern is the economic production of components which can be made—but not economically—by conventional methods.

Investment casting reduces production costs in several ways. For example, the wear on dies used for making soft wax patterns is much less severe than the wear imposed on steel dies used for direct metal pouring. Original precision of the dies can be held for long production runs and, when the dies do eventually wear, they can be replaced very quickly. In the same way, much less time is needed to embody modifications. Routine improvements made necessary by the pressure of competition or arising from production experience can be quickly and cheaply effected.

The greatest saving, however, is in the reduced amount of machining required to finish a component. An investment casting is a precision casting ; its surface finish and dimensional accuracy are such that many machining operations can be eliminated. The outlay for machinery is less, the production time is cut, and the percentage of wastage decreased.

The economies obtainable from the use of investment castings affect all phases of development,

Fig. 9
A cast seal housing being checked for dimensional accuracy and examined for casting imperfections

from prototype construction to full-scale production, and while costs can often be lowered by introducing the process into current production, far greater savings can be made by using investment castings from the outset of a new project.

In common with most production methods the practical limitations of the process are elastic, and the point at which it ceases to be an economic proposition cannot be firmly defined without over-simplification. Investment castings generally yield worthwhile results when the castings weigh less than 5 lb, need an average amount of machining if made by other methods, and are required in quantities of between a few dozen and several thousands. Castings of very simple outline which exceed 10 lb in weight or which are required in quantities of several hundred thousand, are usually unsuitable for production by investment casting.

Summarising the foregoing notes, investment castings can reduce :—

(*a*) the development tooling costs for most small castings by reducing machining time and saving the cost of steel dies for every design change made,
(*b*) the initial tooling costs for the production run,
(*c*) the time between design and delivery of castings,
(*d*) the risk of breakdown during the production run, through reduced machine-tool capacity and reduced likelihood of damage to dies,
(*e*) the cost of new tooling for detail modifications during the production run,
(*f*) the cost, time, and material wastage that occurs when difficult-to-machine alloys are machined down from stock sizes,
(*g*) fabrication times and jigging costs, by enabling complex shapes to be cast in one piece.

Investment castings are not normally an economical proposition :—

(*a*) in direct competition with stampings,
(*b*) in direct competition with drop forgings, except on small runs,
(*c*) in direct competition with screwing machine parts,
(*d*) where the major machine operations can be performed on a turret lathe,
(*e*) where the principal machining can be done by broaching or part milling,
(*f*) where the tolerances are too close for an investment casting.

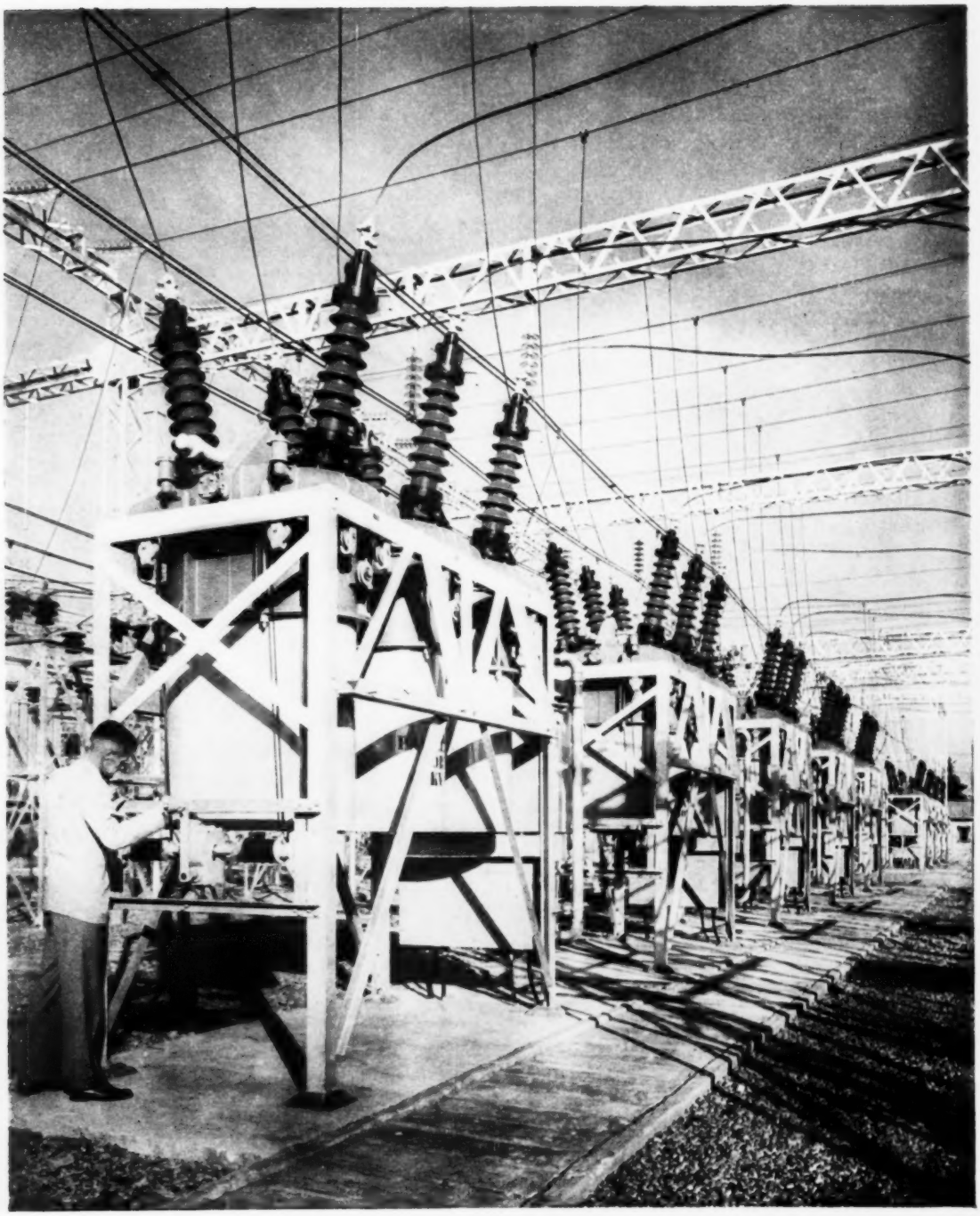
In such cases it is usually as easy to employ sand castings, since the reduction in machining with investment castings will not be sufficient to effect great saving.

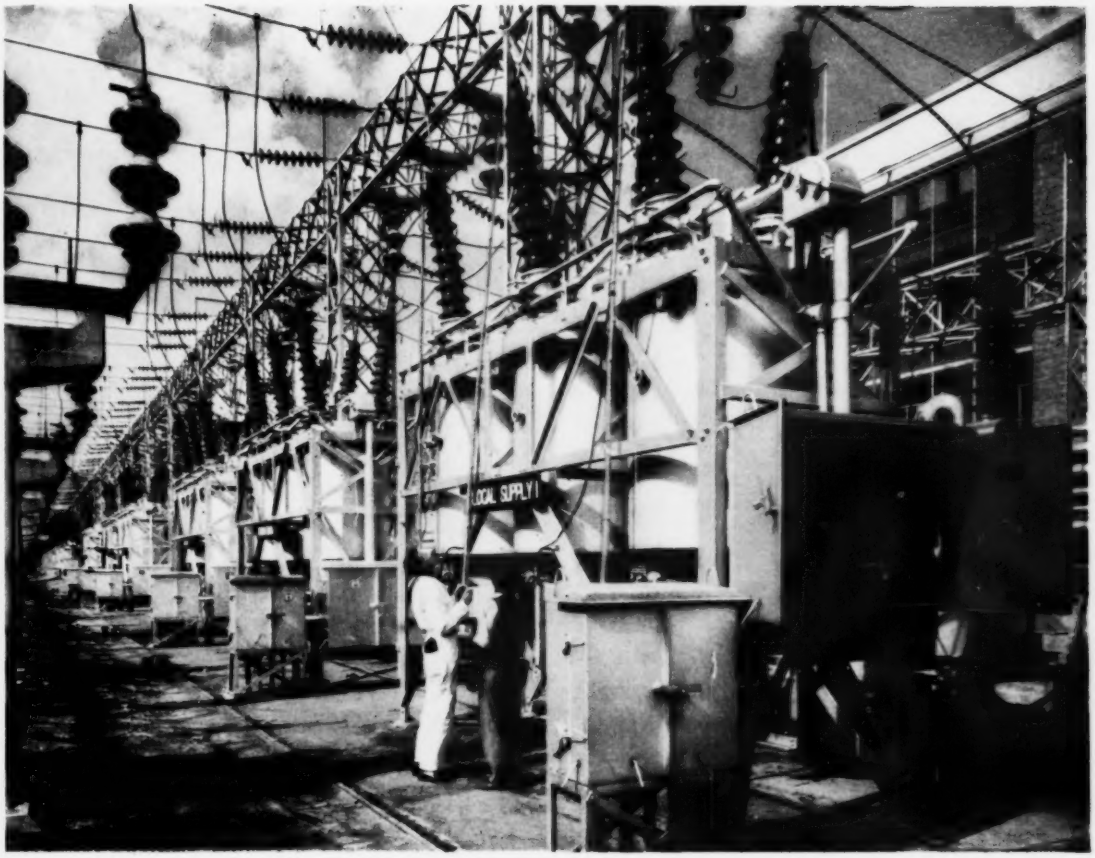
Technical Advantages

Correctly applied, the investment casting process not only effects remarkable economies but also allows considerably more freedom in design. There is virtually no restriction on shape, even multiple re-entrant contours being cast without difficulty. Sections can be cast with thickness as low as ·015 in, and rapid changes of section cast with no more graduation than is necessary to avoid stress-concentration in the structure.

An important consideration is that castings can be made not only in the hard high-fusing alloys such as HRCM, Stellite and HSS. 72, but also in a wide range of metals. In addition, the designer has a choice of surface finishes for his component. The castings are normally finished by shot-blasting, but satin finishing and the fine-grain finish obtained by vapour blasting are available.

The Napier Investment Foundry is a young and growing concern, and its technicians, with first-hand experience of every kind of foundry problem and practice, are forever searching for ways of improving techniques, speeding production and reducing production costs. The manufacture of every new component is carefully considered in the light of past experience, and the aim is always ' the ideal shape, in the ideal material, at an economical price '.





OUTDOOR OIL CIRCUIT-BREAKERS IN SOUTH AFRICA

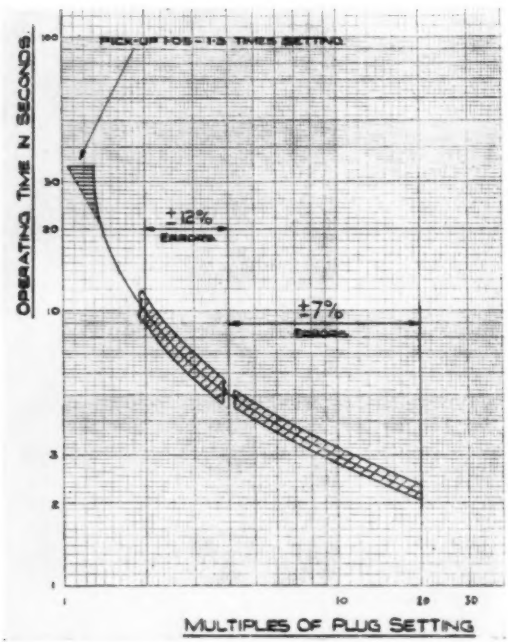
Above: 88 *kV* 2500 *MVA type OKG7 oil circuit-breakers at the Orlando Power Station of the City of Johannesburg Electricity Department. Twenty-three of these breakers are installed at this station and there are over fifty at other sites in South Africa, including the Prospect Switching Station and the new Kelvin Power Station of the City of Johannesburg Electricity Department.*

Left: 40 *kV* 1000 *MVA type OKG4 oil circuit-breakers at the Struben Distribution Station of the Rand Undertaking of the Electricity Supply Commission, South Africa. Altogether there are fourteen of these breakers at this station.*

Application of Inverse-time Overcurrent Relays

By R. W. NEWCOMBE, A.M.I.E.E., Switchgear Engineering Department.

FOR MANY YEARS definite minimum time overcurrent relays have been used extensively in the United Kingdom for the protection of generators, transformers and high voltage and distribution networks, either as the main form of protection or as back-up to the main protection. While these relays have been found adequate for the majority of applications, a need was felt for improved accuracies and for time/current characteristics more closely matched with the thermal characteristics of the equipment to be protected.



Time and pick-up errors, at unity time multiplier

Fig. 1—*Typical limits of accuracy set by British Standard* 142 : 1953 *for an inverse definite minimum time relay*

This article shows how The English Electric Company is meeting these demands by the introduction of a series of relays which will not only make it possible to obtain closer grading but will have improved performance and characteristics.

The following types of overcurrent relays are considered :—

(1) The inverse definite minimum time (I.D.M.T.) relay having British Standard time/current characteristics.
(2) A combined I.D.M.T. relay and high set instantaneous relay.
(3) A definite time overcurrent relay.
(4) A very inverse definite minimum time relay.
(5) An extremely inverse definite minimum time relay.

As some of the terminology in this article may be unfamiliar to many not closely conversant with relay technique, the following definitions may be of value.

Time setting multiplier. A means of adjusting the movable back-stop which controls the travel of the disc and thereby varies the time in which the relay will close its contacts for given values of fault current.

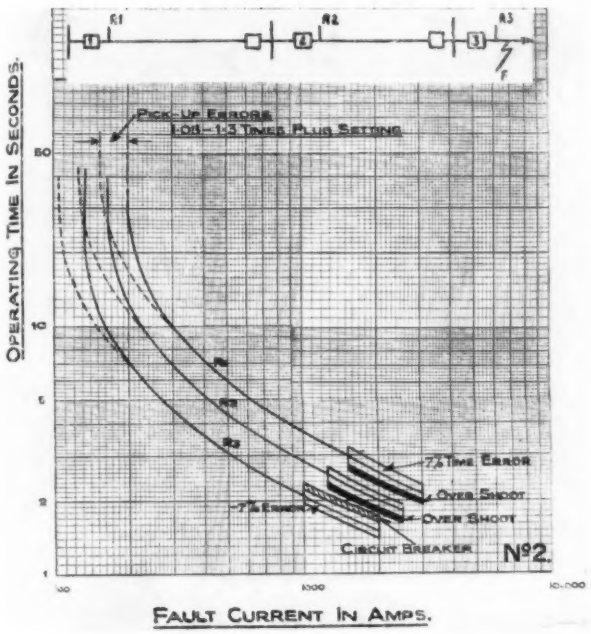
Plug setting bridge. A device providing a range of current settings at which the relay will start to operate.

Pick-up errors. Allowable errors in the current value at which the disc starts to move and at which its contacts close, expressed as a multiple of the plug setting.

Overshoot. The margin of time allowed for the relay disc to travel after the fault has been cleared before it closes its contacts.

Standard I.D.M.T. Relay

Limits of accuracy have been considered by various national and international committees, and Fig. 1 shows a typical example of the limits set by



Minimum grading times at 2,000 amperes for a fault at 'F'.

Relay error R2 and R3	·14 + ·105	= ·245
Over-shoot R2	·1	= ·1
Breaker time at R3	·15	= ·15
Time between R2 and R3		= ·495 second

Relay errors at 10 times at 20 times.

Relay R1	·21	·15
,, R2	·18	·13
,, R3	·14	·11

Relay settings (TSM = time setting multiplier).

R1 = 1·0 TSM 150% plug setting
R2 = ·85 TSM 125% ,, ,,
R3 = ·7 TSM 100% ,, ,,

Current-transformer ratio 100/5

Fig. 2—Application of an inverse definite minimum time relay to a sectioned radial feeder

the British Standards Institution specification B.S.142 : 1953 for the standard inverse definite minimum time relay.

Fig. 2 illustrates the application of such a relay to a sectioned radial feeder, and it will be seen that with the assumed relay settings and B.S. tolerances the minimum permissible time grading between the overcurrent relays at each section circuit-breaker is approximately 0·5 second.

With the increase in system fault current it is desirable to shorten the clearance time nearest the power source in order to minimise damage. It is therefore necessary to reduce the time errors which are now disproportionately large when compared with the clearance time of modern circuit-breakers, and this can only be achieved by improving the limits of accuracy, pick-up and overshoot. All this must be obtained without detriment to the general performance of the relay; in other words, there must be no reduction in the operating torque, or weakening of the damper magnets or contact pressures, and the construction must remain simple and contain the minimum number of moving parts.

While these requirements present considerable difficulties in manufacture due to the variation in material and practical tolerances, the progress made in the 'English Electric' improved relay makes it now possible to discriminate more closely by shortening the margin between both the current and the time settings of the relays on adjacent breakers. This special relay will thus enable the time setting of the relay nearest the power source to be reduced, or alternatively, make it possible to increase the number of breakers in series without increasing the time setting at the power source.

Combined I.D.M.T. and High Set Instantaneous Relay

A further advantage can be gained on long lines or on transformer feeders where the source impedance is small in comparison with the circuit impedance, by adding a high set instantaneous relay to the inverse time relay at each point, making it possible to reduce the tripping time under the maximum short-circuit conditions, and shortening the grading space between each breaker.

Inverse Relays
All relays set at 125%
R1 set at 500A on 0·125 TSM
R2 ,, ,, 125A ,, 0·15 ,,
R3 ,, ,, 62·5A ,, 0.1 ,,
Instantaneous Relays
R1 set at 3000A
R2 ,, ,, 1400A
R3 ,, ,, 500A
CT = current transformer
TSM = time setting multiplier

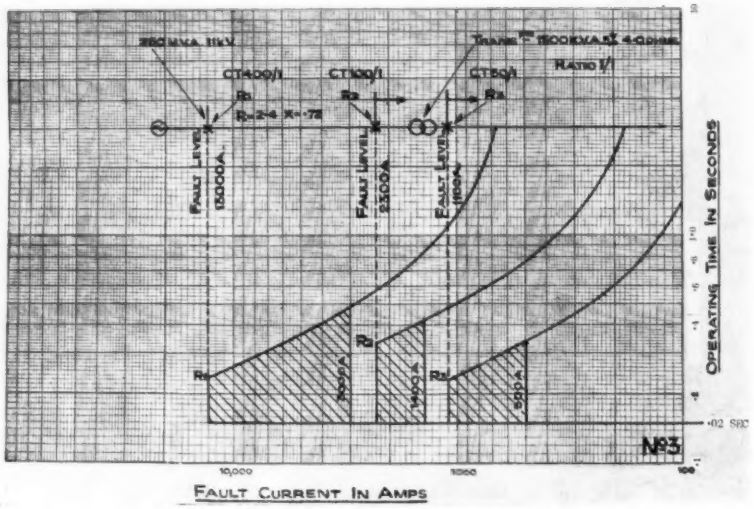
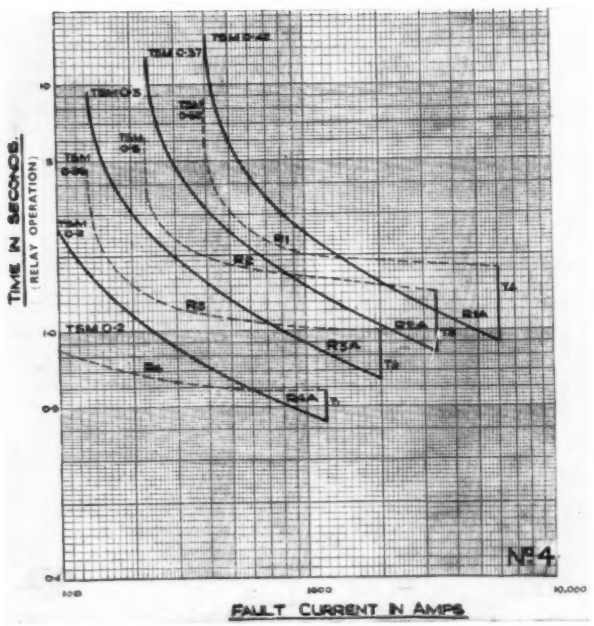


Fig. 3—Characteristics of combined inverse definite minimum time relay and high set instantaneous relay



R1A and R1 set to pick up at 300A
R2A ,, R2 ,, ,, ,, ,, ,, 175A
R3A ,, R3 ,, ,, ,, ,, ,, 100A
R4A ,, R4 ,, ,, ,, ,, ,, 57·5A
Time between breakers 0·4 second
——— Inverse time relay
------ Definite time relay
TSM = Time setting multiplier

Fig. 4—Comparative characteristics of definite time relay and inverse definite minimum time relay

The effect of the instantaneous element is to reduce the operating time in the shaded areas shown in Fig. 3 to 0·02 second and, provided the generating capacity remains constant, it is possible to obtain high-speed protection over a very large portion of the circuit.

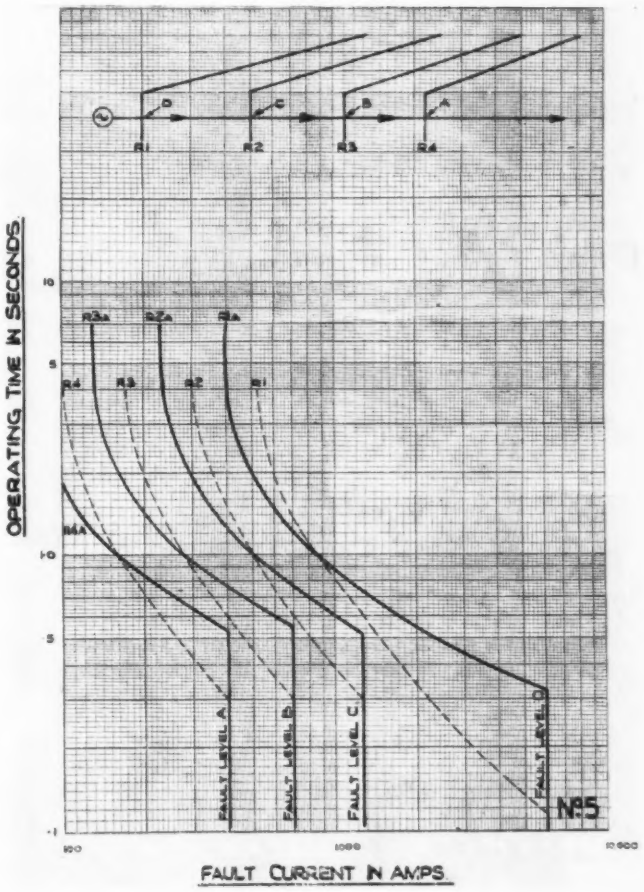
The new 'English Electric' relay incorporates this instantaneous element which has been designed to be insensitive to the initial transient present at the moment of fault. This element can be incorporated in the same relay case with the standard inverse time overcurrent relay, so that replacing a standard relay by the new type involves no extra panel space or drilling.

Definite Time Overcurrent Relay

The 'English Electric' definite time relay provides a ready means of co-ordinating several relays in series where the system fault current varies very widely due to changes in source impedance, as there is a relatively small change in time with the variation of fault current. The characteristics of this relay are obtained by an internally mounted auxiliary current-transformer which saturates immediately after the current reaches the pick-up value.

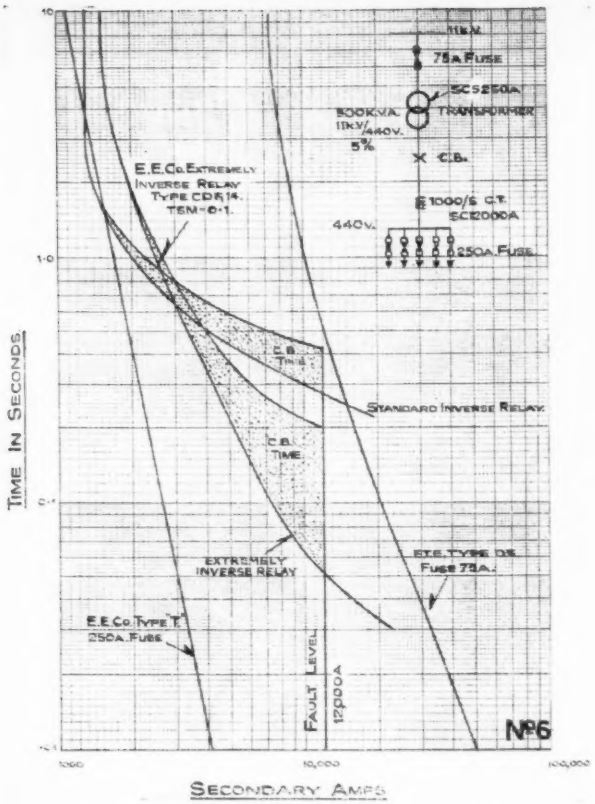
The characteristics of this relay are shown in Fig. 4, together with those of the standard inverse time relay having a definite minimum time characteristic, from which it will be seen that an advantage is gained by the inverse relay at the higher values of fault current, whereas the definite time relay has the advantage on the lower current values. The time difference at the maximum fault conditions is indicated by the vertical lines T1, T2, T3 and T4.

While this relay can be used in a very large number of overcurrent applications, it cannot, however, replace the standard inverse definite minimum time relay or the very inverse relay where it is possible to take advantage of the reduction of fault current as the distance from the power source increases.

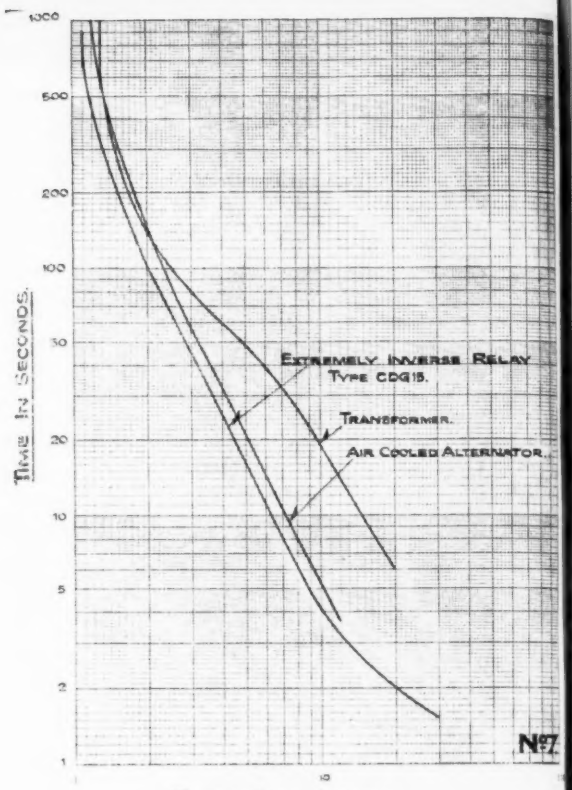


R1A and R1 set to pick up at 300A
R2A ,, R2 ,, ,, ,, ,, ,, 175A
R3A ,, R3 ,, ,, ,, ,, ,, 100A
R4A ,, R4 ,, ,, ,, ,, ,, 57·5A
Time setting multiplier 0·15 on all relays
------ Very inverse characteristics
——— British Standard characteristics

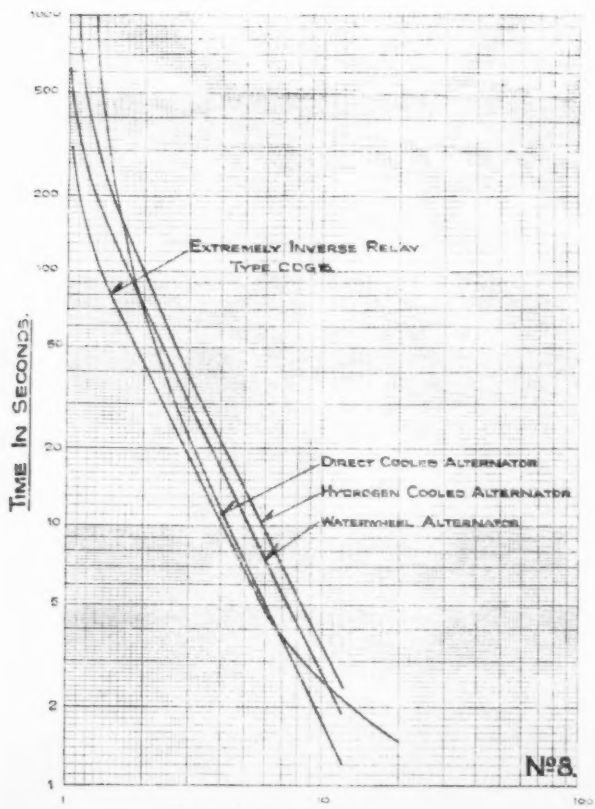
Fig. 5—Characteristics of very inverse relay and comparison with those of a standard inverse definite minimum time relay



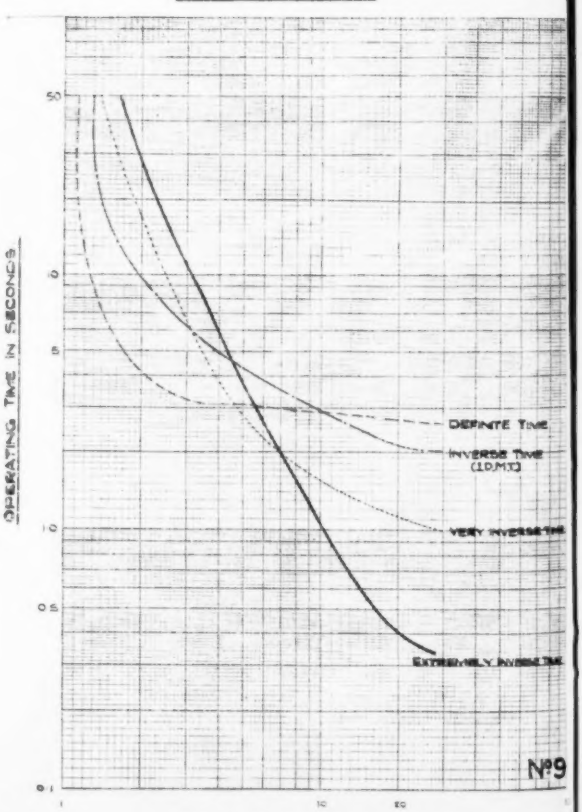
SECONDARY AMPS



TIMES FULL LOAD



TIMES FULL LOAD



MULTIPLES OF PLUG SETTINGS

All curves in Fig. 9 shown at unity multiplier

The Very Inverse Overcurrent Relay

The very inverse type of overcurrent relay is particularly suitable in cases where there is a substantial reduction of fault current as the distance from the power source increases. The characteristics of this relay are such that its operating time is approximately doubled for a reduction in current from 7 to 4 times the relay plug setting multiplier. This permits the use of the same time setting multiplier for several relays in series.

In the example shown in Fig. 5 it has been assumed that the maximum fault current at substations C, B and A is 1,225, 700 and 400 amperes respectively, i.e., in the ratio of 7 to 4 between successive substations. It is seen that with the stated relay settings a difference of 0·3 second in the tripping times of adjacent circuit-breakers is obtained although all relays have the same time multiplier setting of 0·15.

A comparison is given in the same figure to show the impossibility of obtaining the same time settings using a standard I.D.M.T. relay.

This very inverse relay not only reduces the tripping time between breakers but invariably allows a lower time multiplier setting to be employed and, as the errors are only 7% of the minimum operating time, the margin between the time grading steps can be reduced. As an illustration, if the standard inverse time relay R1A had a time multiplier setting of unity, the errors at 10 times the setting would be 7% of 3 seconds which, when added to the errors on the relay at the adjacent substation, plus the breaker time and relay overshoot time, would be 0·21 + 0·21 + 0·15 + 0·05, which is equal to 0·62 second. If, on the other hand, the time setting multiplier were set at 0·1, then the relay time errors would be reduced to 1/10th, so that the time interval between adjacent breakers would now be 0·021 + 0·021 + 0·15 + 0·05, which is equal to 0·24 second.

While advantage of this reduction in time can be taken on the standard inverse relay, it is still more effective on the very inverse relay, since the time at 10 times the relay setting is only 1·5 seconds at unity multiplier and only 0·15 second on the 0·1 time multiplier ; thus the time errors are only 50% of the standard relay errors, and the overshoot and breaker time become the predominant factors.

While the maximum time for overshoot quoted in the B.S. specification is 0·1 second, the 0·05 second given in the above example is the maximum value acceptable on any 'English Electric' relay at unity multiplier ; furthermore, this value decreases at the lower time multiplier settings as the disc momentum is smaller due to the reduced distance of travel.

It should be noted that the foregoing values are given on the assumption that the relay errors between adjacent breakers are positive on the one relay, and negative on the other. Furthermore, it is not possible to take advantage of the reduction in the time errors unless the current settings are wide enough to take care of the variation in pick-up values as illustrated in Fig. 2.

Extremely Inverse Overcurrent Relays

A further 'English Electric' inverse relay has extremely inverse time characteristics, the time being inversely proportional to the square of the current ; this makes it suitable for the protection of distribution feeder circuits where the feeder is subject to peak currents on switching in, as would be the case on a power circuit supplying refrigerators, pumps, water heaters, etc. which remain connected after an interruption in the supply.

It is sometimes difficult to find an inverse relay having characteristics suitable to grade with fuses and at the same time to remain inoperative on switching current. This problem has been successfully solved by the long time characteristics of the extremely inverse relay at normal peak values. Fig. 6 gives typical curves showing the application of this relay on an 11 kV system supplying a

Fig. 6—Typical curves showing application of extremely inverse relay on a system supplying a distribution transformer through an H.V. fuse

Fig. 7—Characteristics of an extremely inverse relay compared with the thermal characteristics of a generator/transformer unit

Fig. 8—Characteristics of extremely inverse relay compared with the thermal characteristics of various types of alternators

Fig. 9—Comparison between characteristics of various types of inverse relays

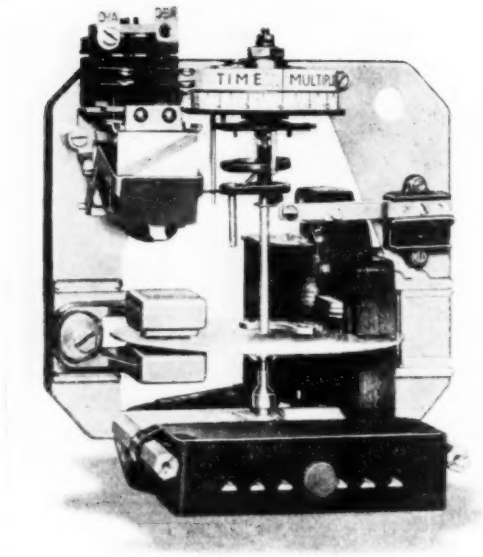


Fig. 10—An 'English Electric' relay typical of those described

out of service unnecessarily, but to trip before any damage can result from abnormal conditions occurring on the power system.

Consideration is being given to the possible use of an extremely inverse relay for the protection of generators against overload and internal faults. The average generator under fault conditions reaches its sustained value of short-circuit current in 3 or 4 seconds, this value being often below twice the generator's continuous current rating, depending upon the value of excitation.

In the past, difficulties have arisen in the correct selection of suitable relay settings, using the standard I.D.M.T. relay, as it is necessary to select a setting which not only discriminates with over-current relays on the system and is inoperative on momentary overloads, but is operative on the sustained short-circuit current of the generator.

An extremely inverse relay applied to a generator/transformer equipment is shown in Fig. 7. It will be apparent that the characteristics are such that the relay gives adequate protection at the lower values of overload at a time corresponding to the distribution transformer through a high-voltage fuse, and indicates a difference of 0·45 second between the operation of the relay and the clearing time of the fuses at the maximum fault level, which allows for the circuit-breaker time and variations in the fuse operating time.

This relay can also be used in conjunction with a negative phase sequence network for the protection of large generators, as its characteristics can be made to follow closely the permissible negative phase sequence current of any generator by varying the time setting multiplier and/or current setting, giving a range of adjustment of $I^2t = 5$ to 30. The characteristics of this relay permit such close settings as to prevent a generator being taken

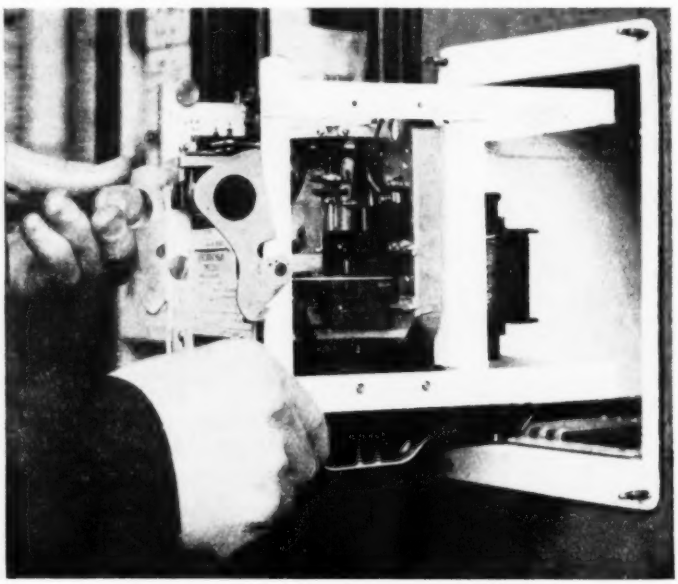


Fig. 11—Withdrawable features of relays to simplify testing and maintenance

safe thermal rating of both the generator and the transformer, while leaving ample time for discrimination with other overcurrent relays on the system. Fig. 8 compares the characteristics of such a relay with those of various types of alternators.

Summary

Fig. 9 compares the characteristics of the various types of inverse relays referred to in this article. It should, however, be noted that all these curves are shown at the unity multiplier. Since the characteristics of the extremely inverse relay will depend to some extent on its application, only one such curve is shown.

Fig. 10 shows a relay typical of those mentioned. The simplicity of the movement will be noted, and by minor variations to this basic design the several characteristics described in this article can be obtained. The relays are made in single pole or triple pole units and vertical or horizontal patterns.

Fig. 11 illustrates the withdrawable features available which simplify testing and maintenance.

'English Electric' Direct Current Heavy Duty Mill Type Auxiliary Motors

By H. TURNER, Traction Machine Design Department.

EARLIER TYPES

MOTORS FOR HEAVY DUTY rolling mill auxiliary drives were manufactured as early as 1904 at the Dick Kerr Works, Preston. After the formation of The English Electric Company in 1918, a range of octagonal cast frame D.C. auxiliary mill motors with sleeve bearings, known as the MM type, was produced at the Bradford Works. This range was continued until 1934 in outputs from 15 h.p. to 100 h.p.

In 1934 a new range was introduced superseding the cast frame motors. The new machines incorporated rolled steel frames and were known as the CM type. In the absence of any equivalent British standard they were built to the recommended standard dimensions of the American Association of Iron and Steel Engineers (A.I.S.E.). The first machines were known as 'long standard' type due to the comparative length of the armature to the diameter. Six long-standard frame sizes were made, designated CMR 6, 8, 10, 12, 14 and 16, which were mechanically interchangeable with the American frames 4, 6, 8, 10, 12 and 14.

The American standard was subsequently modified, resulting in a shorter machine, and in 1945 nine 'English Electric' CMR frames were added to correspond to the new specification. These motors were known as the 'short standard' range, and the new frame sizes were CMR 4, 5, 7, 9, 11, 13, 14½, 18 and 18½, interchangeable with the American frames 3, 4, 6, 8, 10, 12, 14, 16 and 18.

The following additional CMR sizes were also made :—

(*a*) Long standard CMR 15, 3 inches shorter than CMR 16.

(*b*) Short standard CMR 17, 3 inches shorter than CMR 18.

(*c*) Short standard CMR 19, interchangeable with American frame 20.

TABLE I

MAXIMUM ONE-HOUR RATINGS OF CMR RANGE LONG STANDARD AND SHORT STANDARD MILL MOTORS

Size	H.P.	Full-load r.p.m.				WR²	Size	H.P.	Full-load r.p.m.				WR²
		200/250 volts		400/500 volts					200/250 volts		400/500 volts		
CMR	75°C	Series	Compd.	Series	Compd.	lb. ft²	CMR	75°C	Series	Compd.	Series	Compd.	lb. ft²
4	7½	800	875	850	900	4	13	50	500	520	500	520	50
5	10	725	775	750	800	5	14*	70	500	520	500	520	64
6*	10	725	775	750	800	5	14½	75	460	480	460	480	110
7	15	650	700	600	700	8·5	15*	75	460	480	460	480	115
8*	16·5	600	650	600	650	9·5	16*	90	420	430	410	420	125
9	25	575	625	575	625	16·5	17	105	400	400	390	390	205
10*	25	500	550	500	550	19	18	130	400	400	375	375	230
11	35	525	550	525	550	30	18½	150	400	400	375	375	300
12*	45	500	525	500	525	36	19	180	400	400	350	350	440
							20	210	400	400	350	350	485

* *Long standard frames.*

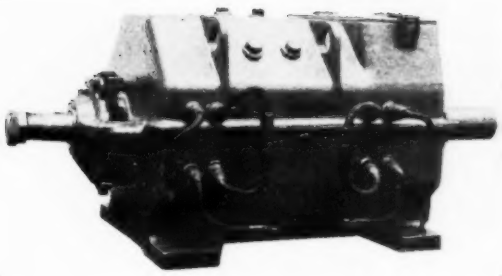


Fig. 1—An early auxiliary mill motor of the MM type, with octagonal cast steel frame

(*d*) CMR 20, 3 inches longer than CMR 19 and larger than any American short standard type.

Table I gives the maximum one-hour ratings of the CMR range of long standard and short standard motors, based on the standard temperature rise of 75° C by thermometer.

The latest development in mill type motors was in 1946 when a new compact range, known as the '600 range', was standardised by the A.I.S.E. This standard used the same basic dimensions as the 'short standard' but increased the horse-power of a given frame to that of the next larger frame. Thus the output from, say, a frame 612 motor was equal to that which was obtainable from a frame 14 motor of the 'short standard' range. A new frame size 618 was introduced with an output of 200 h.p. The 'English Electric' frames run from CMR 1602 to CMR 1618, which correspond to the American frame numbers with the prefix '1' added, and include also the larger CMR 1620 size which is not yet covered by the American specification.

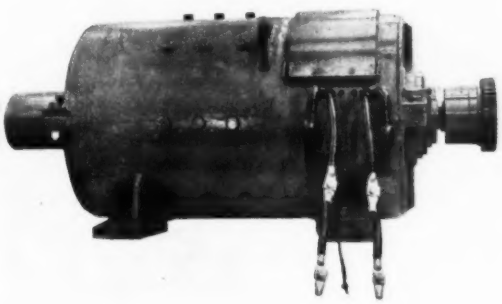


Fig. 2—A 'long standard' CM type motor with roller bearings and cable tails

The majority of new installations use the 600 range machines, but long standard and short standard motors are still manufactured to suit the requirements of users who had adopted these previous ranges as their standard.

More detailed descriptions follow of the machines that have been mentioned.

MM Type

Although from the manufacturing aspect the MM motors are obsolete, many are still in use and the following particulars may be of interest in relation to the modern CMR 1600 type described later.

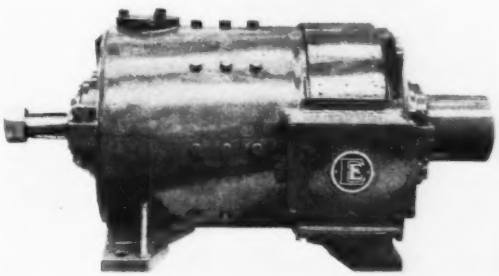


Fig. 3—A 'short standard' CM type motor with roller bearings and terminal box

A typical MM motor is illustrated in Fig. 1, with its robust totally-enclosed dust and splash proof octagonal cast steel frame split above the horizontal centre line. These motors were fitted as standard with white-metal lined sleeve bearings, the housings of which were also split horizontally.

A feature of these early motors which has been retained on all subsequent designs was that the machine could be turned end for end if the driving shaft should be damaged. This was achieved by making the motors double-ended with all fixing dimensions symmetrical about the vertical centre

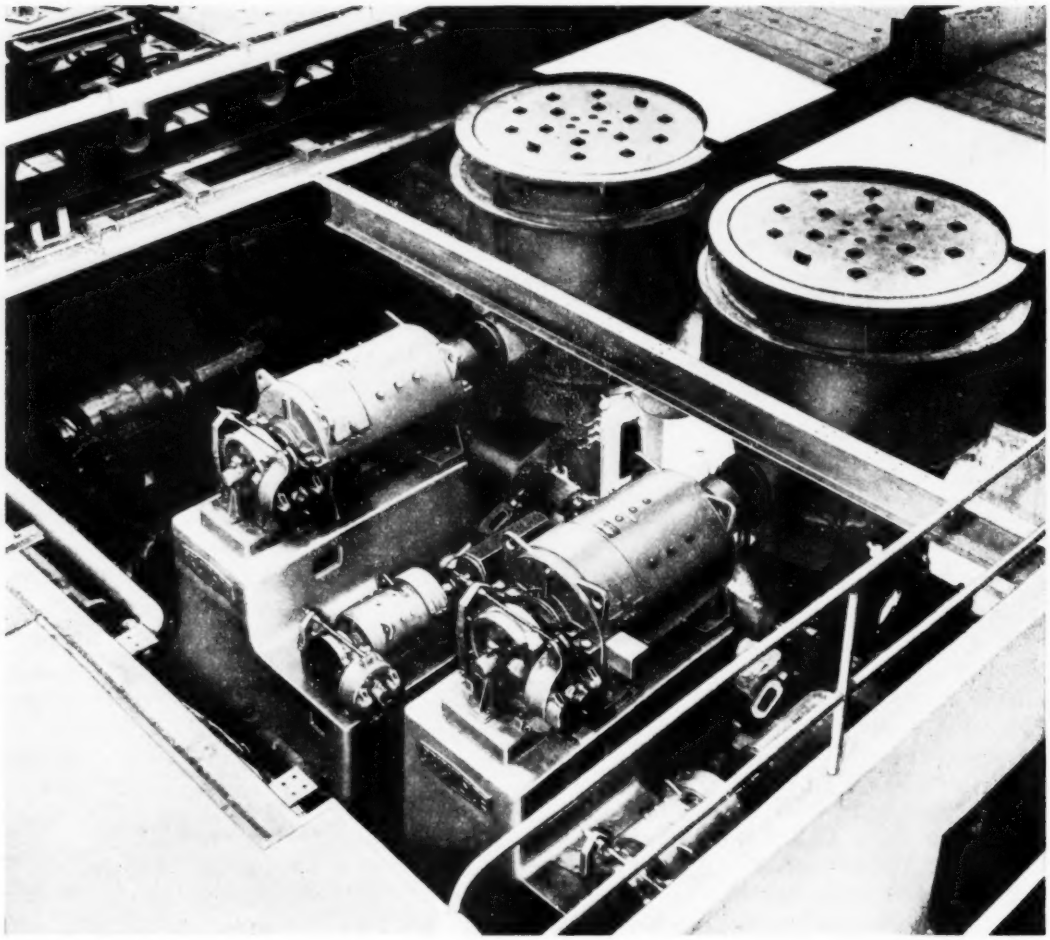


Fig. 4—Auxiliary mill motors of the CMR 1600 range driving coilers in a British steelworks

line. The shaft end not in use was protected by a steel cover.

The split frame was arranged so that the top half could be removed for inspection or maintenance without disturbing the internal field or armature connections. This is another important feature which has been retained on all subsequent mill motor designs.

MM mill motors were available in seven frame sizes with ratings from 15 to 100 h.p. at 600 and 500 r.p.m.

CM Type

When designing the CM range of motors conforming to the A.I.S.E. standard, the opportunity was taken to change from a cast construction to frames fabricated of rolled steel. A further innovation was the introduction of roller bearings as an alternative to the white-metal sleeves of the earlier range. The suffix R or S was used after the CM type symbols to indicate roller or sleeve bearing machines.

One of the advantages of the fabricated

construction was the ease with which the fixing dimensions could be altered if required. Though these machines were then built to American standard dimensions, certain users required motors which were interchangeable as far as possible with MM and other non-standard types. The modifications involved could generally be achieved by a simple alteration to the frame drawings. Such adaptations would have been too costly with a cast frame construction due to the need for new patterns.

Further, perhaps the main advantage of the fabricated frame compared with the casting was the small tolerance which the designer needed to allow for material irregularities affecting both mechanical stress, and magnetic circuit, calculations. The fabricated frame can also be easily machined throughout the bore of the magnetic section. This is uneconomic with cast octagonal frames where rough surfaces for supporting field coils have to be left unmachined and are therefore subject to wide tolerances.

Although the motors of the CM range could be manufactured with either sleeve or roller bearings, so few of the CMS sleeve bearing machines have been supplied that only the type CMR roller bearing motors need be considered in this article.

Roller bearings are much more suitable for mill service than the white-metalled sleeves. The motors are frequently installed in inaccessible positions, and though some are regularly maintained, many receive very little servicing. As the roller bearings are grease-lubricated and are enclosed in dust-tight cartridge-type housings, they are more suited to infrequent attention. The bearings are manufactured to fine limits and will run for many years without measurable wear, ensuring greater accuracy of alignment. Starting torques are also much reduced since the friction loss of a roller bearing is only about 10% of that with the best sleeve bearing. The use of roller bearings also results in a shorter overall length than that of the sleeve bearing motor.

A typical long standard CMR motor with cable tails is shown in Fig. 2, and a short standard machine fitted with a terminal box in Fig. 3. The ratings of the CMR motors have already been given in Table I.

THE CMR 1600 RANGE

The modern 'English Electric' auxiliary mill motors are represented by the CMR 1600 range to which the following description applies but is in most respects equally applicable to the long standard and short standard CM motors previously mentioned.

The dimensions and ratings of the CMR 1600 range motors comply with Standard No. 1 of the American Association of Iron and Steel Engineers. As already mentioned, machines to this standard are commonly known as '600 range'. The American standard gives ratings for D.C. supplies of

TABLE II

OUTPUTS AND SPEEDS OF CMR 1600 RANGE TOTALLY ENCLOSED MILL MOTORS

Frame CMR	A.I.S.E.* motor frame	One-hour, 75 C rise, or Continuous, 75 C rise (force vent.) h.p	Full-load r.p.m. Series	Full-load r.p.m. Comp. or shunt	Adjustable speed
220/230 volts					
1602	2	5	900	1025	1025–2050
	602	7½	800	900	900–1800
1603	603	10	725	800	800–2000
1604	604	15	650	725	725–1800
1606	606	25	575	650	650–1950
1608	608	35	525	575	575–1725
1610	610	50	500	550	550–1650
1612	612	75	475	515	515–1300
1614	614	100	460	485	485–1200
1616	616	150	450	460	460–1150
1618	618	200	410	420	420–1050
1620	—	250	375	375	375–1000
440/460 volts					
1602	2	5	1015	1150	1150–2050
	602	7½	935	1025	1025–1800
1603	603	10	810	885	885–1800
1604	604	15	725	800	800–1800
1606	606	25	635	700	700–1600
1608	608	35	585	625	625–1400
1610	610	50	530	585	585–1300
1612	612	75	510	550	550–1220
1614	614	100	475	500	500–1160
1616	616	150	460	460	460–1100
1618	618	200	415	415	415–1000
1620	—	250	375	375	375–900

* *American Association of Iron and Steel Engineers.*

230 volts and alternatively 550 volts. The CMR machines, however, are designed for the D.C. supplies normally used in Britain. The '600 range' outputs and speeds for 230 volts can be obtained on standard CMR 1600 frames over the range 220/230 volts, and outputs for 550 volts over the range 440/460 volts.

Table II gives the standard motor ratings for the two voltage ranges. The same outputs apply for totally enclosed one-hour rated machines or forced ventilated continuously rated machines.

Frame

The CMR 1600 type mill motor has, like its predecessors, a very robust frame fabricated from high magnetic quality rolled steel. The frame is cylindrical in form, and is split just above the horizontal centre line. The top half is arranged for complete removal, in preference to hinging on the bottom half, as a crane is necessary in any case for all but the smallest motors.

Fig. 5 shows a motor with the top half removed and turned over. For this operation it is not necessary to disturb any internal connections or wiring, as the connections completing the field and armature circuits are made outside the frame as shown in Fig. 6. The standard terminal arrangements are plain cable tails as on this illustration, or alternatively a cast terminal box. When required, a further alternative is to bring the connections to terminals covered by a sheet steel hood open on the underside.

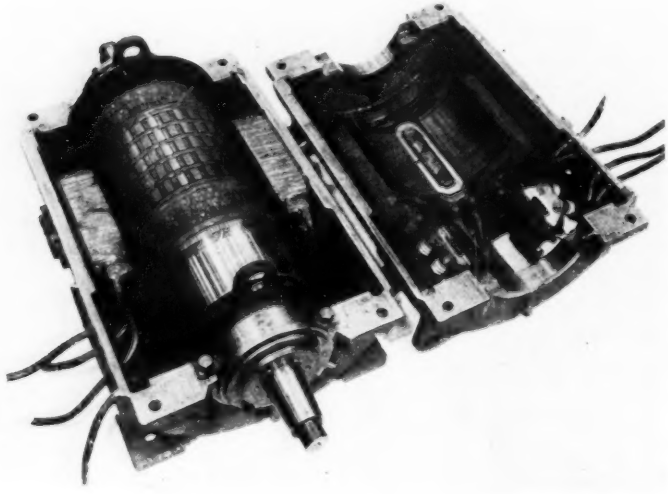


Fig. 5—CMR 1600 range motor with top half removed and inverted

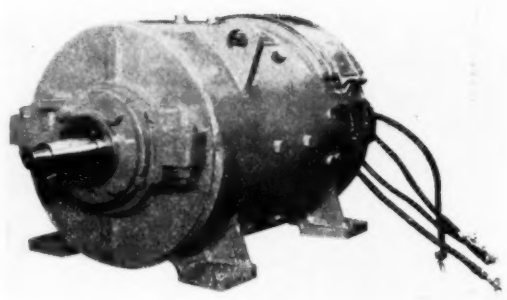


Fig. 6—Totally enclosed CMR motor, showing external connections and cable tails

Enclosure

Total enclosure with a one-hour rating is standard, but when continuous rating is required the same output can be obtained continuously by forced ventilation. Naturally ventilated machines are also available, but the demand for such motors in steel mills and for crane duty is small.

Fig. 6 shows a typical totally enclosed motor. The air is circulated within the frame and through axial ventilation ducts in the armature core by a steel fan at the back of the armature. The heat from the armature is thereby transferred to the inner surfaces of the frame and bearing housings, whence it passes to the atmosphere by natural radiation and conduction. The provision of the circulating fan greatly reduces hot spots in the armature and field windings and thus enhances the continuous rating of the machine for a given maximum temperature rise.

Examples of forced ventilated motors are shown in Figs. 7, 8 and 9. The air supply can be produced by a common fan and duct system, but where the layout permits, an alternative arrangement is to mount the motor-driven fan unit on the mill motor frame so that it blows air directly into the inlet duct. After passing through the machine the air exhausts to atmosphere through automatic sheet steel louvres which open when the fan is running and close when it is stopped, thus preventing dirt entering the motor when it is not in operation (Figs. 7 and 9). For mill service it is normal to filter the ventilating air before it passes into the frame. When the ventilating fan is mounted on the motor, the filter is built into the intake as shown in Fig. 9.

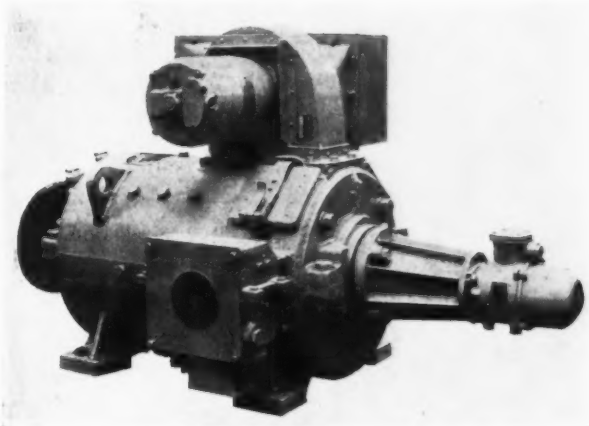


Fig. 8—Forced ventilated CMR machine with motor-driven fan and filter, and tacho-generator on adaptor over shaft

Bearings

Dust-tight steel cartridge type housings contain the roller bearings. The housings fit into machined seals on the frame ends and are positively secured to the lower frame by bolted-in keys (see Fig. 5). The top half of the frame then clamps the bearing cartridges between itself and the lower half.

Each bearing housing has a lifting lug and feet so that the complete armature can be lifted as a unit and placed on the floor without damage to the windings (see Fig. 10).

The bearing assembly is so designed that the housings complete with rollers and outer race can be withdrawn from the shaft, leaving the inner race in place. This ensures that the fit of the inner and outer races can be left undisturbed. The inner race may readily be removed if necessary.

The roller bearings are grease lubricated, with labyrinths in the housings to prevent leakage of lubricant. Tecalemit nipples are provided for greasing the bearings. A grease overflow passage leading to an opening in the frame adjacent to the nipple serves to indicate excess application of grease and prevents grease entering the inside of the motor. Fig. 11 shows these features.

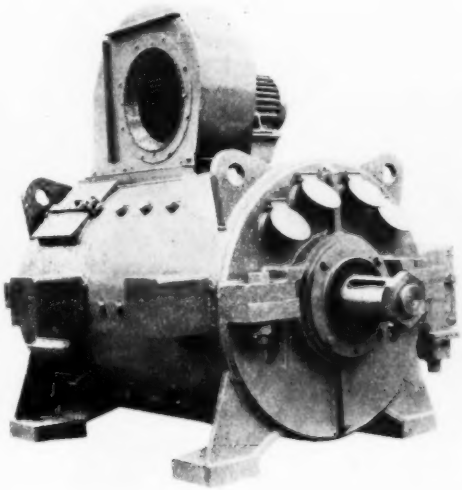


Fig. 7—Forced ventilated CMR machine with motor-driven fan, and automatic exhaust louvres open

Armature

Large diameter shafts of high grade nickel chrome molybdenum steel to a rigid specification are provided on all CMR 1600 motors.

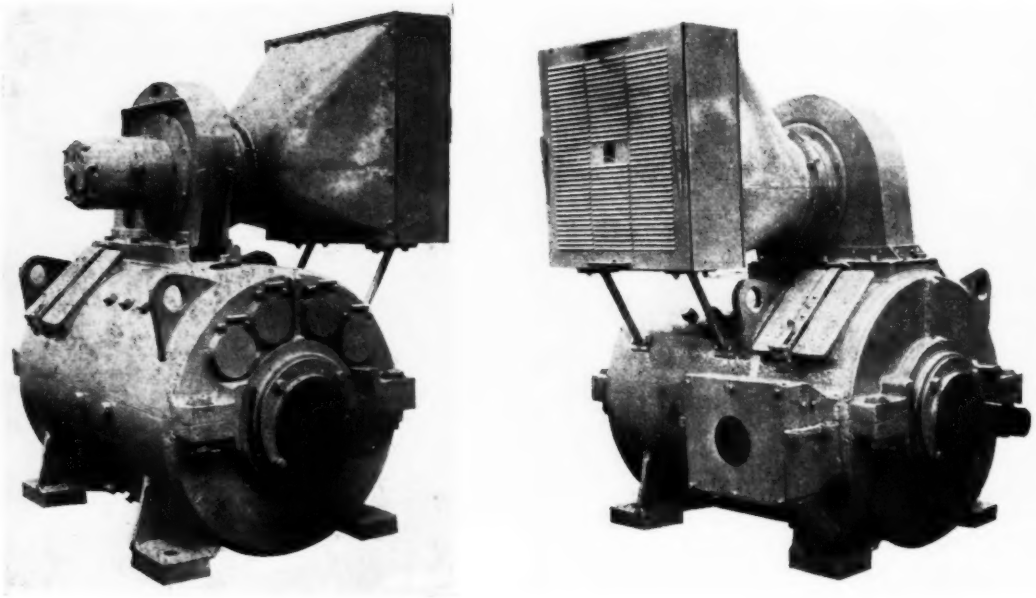


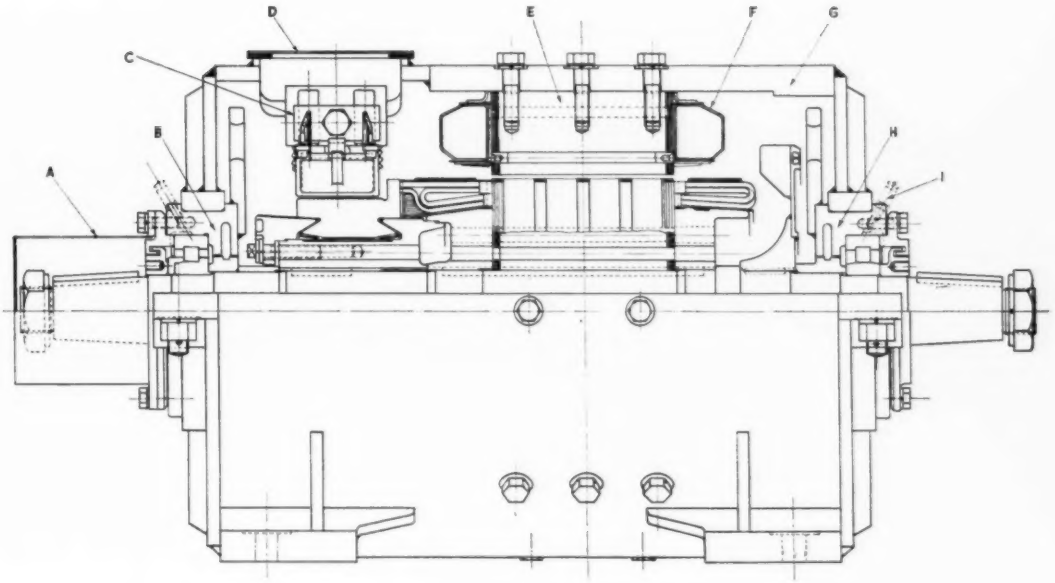
Fig. 9—Two views of a forced ventilated CMR machine with motor-driven fan and filter, the left-hand view showing the exhaust louvres closed

On the larger machines the armature and commutator are built on to a steel sleeve. This sleeve is pressed on the shaft without a keyway and enables the shaft to be withdrawn without disturbing the windings. The smaller sizes have the armature laminations mounted directly on the shaft with a shallow keyway to ensure correct alignment; on these sizes the commutator is also mounted directly on the shaft. Special bolts are available for clamping the armature of the smaller machines when it is necessary to withdraw the shaft.

The commutator construction is such as to maintain a true surface under a wide temperature range. The commutator risers are integral with the bars, and a large wearing depth is allowed. The larger commutators are wedge-bound and bolted, permitting high peripheral speeds. Each mica vee ring is treated with red anti-tracking enamel forming a smooth glossy surface to prevent dust accumulation, and a large creepage distance is allowed.

Single-turn armature coils are insulated with mica tape, and multi-turn coils are constructed of asbestos covered copper strip. The conductors forming a coil are insulated with mica wrap covered with woven glass tape and finally hot pressed to size. The coils in their slots are heavily banded with steel wire soldered with pure tin.

Fig. 10—Armature and roller bearings with lifting lugs and feet



A. Steel cover over unused shaft end.
B. Grease overflow in lower half of bearing.
C. Brush holders.
D. Dust-proof cover.
E. Poles bolted to yoke.
F. Heat-resisting glass and mica insulation.
G. Fabricated steel yoke split slightly above horizontal centre line.
H. Cartridge-type bearing housings, identical at each end, with labrinths to retain lubricant and exclude dirt.
I. Tecalemit grease nipple in lower half of bearing housing.

Fig. 11—*General arrangement of typical CMR* 1600 *range motor*

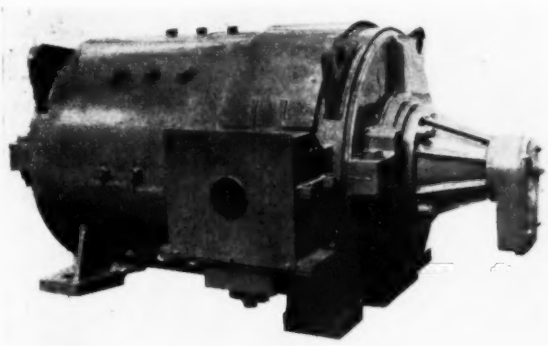


Fig. 12—*Totally enclosed CMR motor with over-speed device on adaptor over shaft*

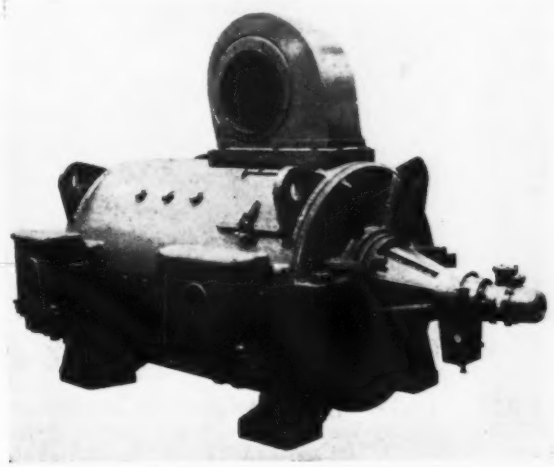


Fig. 13—*Forced ventilated CMR motor with over-speed device and tacho-generator mounted together on adaptor over shaft*

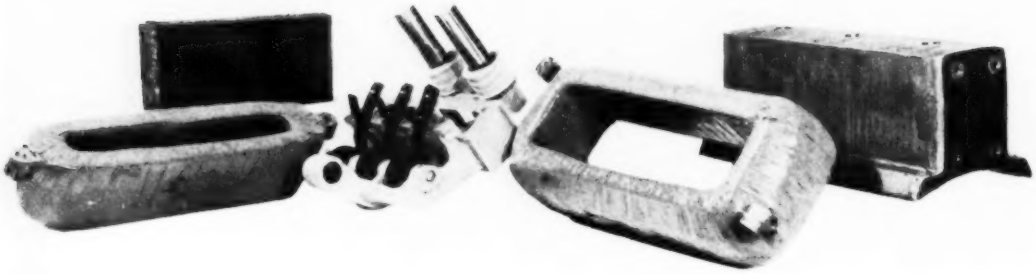


Fig. 14—Typical set of poles and field coils, including brush box assembly

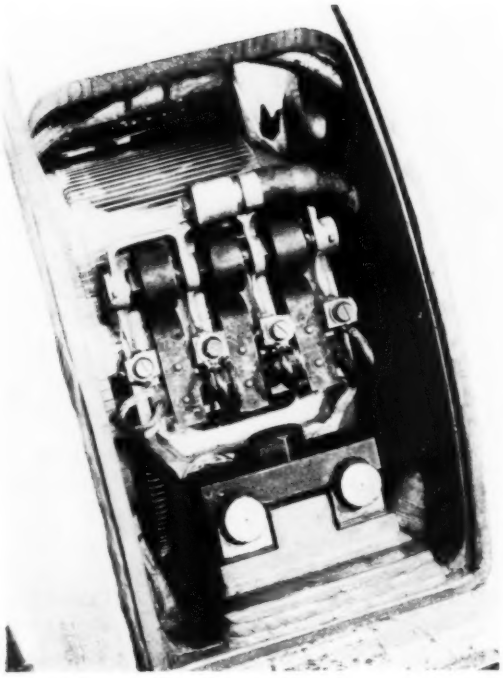


Fig. 15—Brush box and method of support

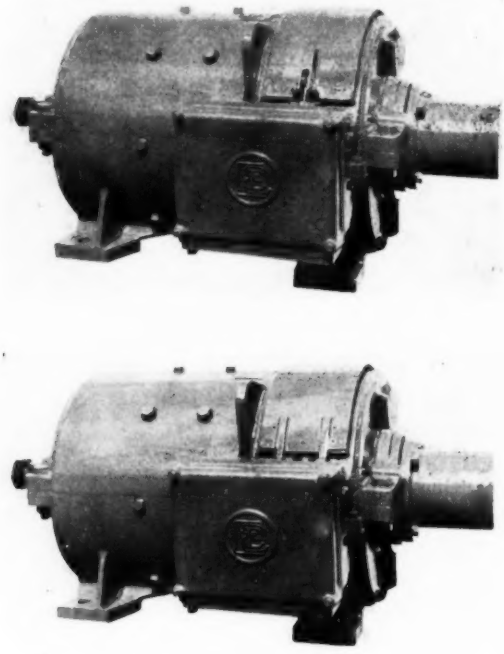
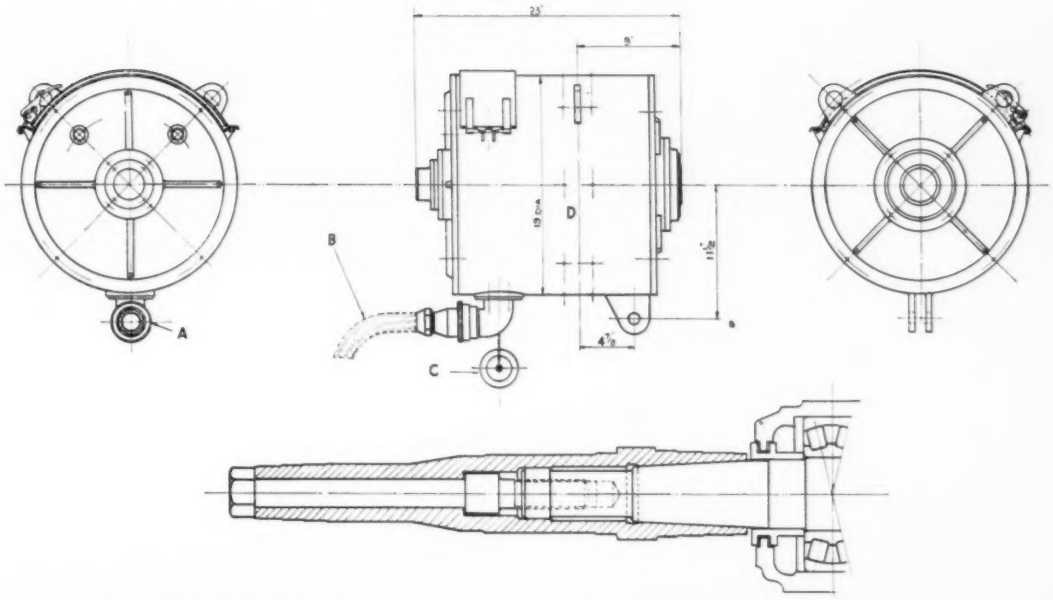


Fig. 16—Two views of a CMR motor, showing alternative positions of commutator inspection cover



A. 6-pin watertight plug and socket.
B. Flexible conduit.
C. Dust cap.
D. Centre-line of armature core.

Fig. 17—General arrangement of CMF type floating frame motor

The complete armature is designed for a low inertia suitable for rapid reversal and acceleration. Fillets of large radius are machined at all changes in shaft diameter to ensure maximum strength.

A tacho-generator or a mechanical over-speed device can be driven by the shaft at the non-driving end. A fabricated cone-shaped steel adaptor is fitted over the shaft to support these accessories, which are shown in Figs. 8, 12 and 13 fitted separately and together.

Poles

All CMR 1600 motors are fitted with four laminated main poles of large magnetic section, and four laminated interpoles, all bolted to the frame.

Series and interpole field coils are formed of flat copper strip insulated between turns with asbestos paper, except for the smallest motors in which small strip is used covered with glass braid. Shunt coils and the shunt portion of compound coils are wound with double glass covered copper wire. The complete coils are heavily insulated with micanite and woven glass tape and then vacuum impregnated. This method provides solid moisture-proof coils, free from air pockets and of good heat conducting quality. The coils are rigidly held between seats on the pole tips and the frame by strong spring washers which ensure freedom from vibration and even pressure distribution. Brass tapered socket type terminals are fitted for good electrical contact and easy replacement.

Fig. 14 shows a set of typical poles and field coils.

Brush Gear

Traction motor principles are followed in the design of the brush gear, with the consequent strength and rigidity for good brush contact under all conditions of vibration and shock. A brush

holder can be removed by loosening one bolt, and provision is made for easy radial adjustment of the brush box to allow for commutator wear. The spring tension on the pressure fingers is easily adjusted, and a heavy flexible copper lead connects the finger to the body of the brush box in addition to the pigtails on the carbons. These flexible leads can just be seen beneath the springs in Fig. 14.

A typical brush box assembly is included in Fig. 14, and the method of supporting the box is shown in Fig. 15.

The cover over the commutator inspection opening is held in place by a single lever-operated catch on the cover itself. The cover can be fitted with the catch on either side of the motor, which is very convenient when the motor is installed close to a wall, for example. Fig. 16 shows a motor with the cover in the alternative positions.

GENERAL

Changing Requirements

The majority of the early 'English Electric' auxiliary D.C. mill motors were series wound. This was probably a legacy from traction practice in which series machines were the rule. To-day, however, most of the motors are shunt or compound wound, except for crane duty where the series characteristic is still invariably required.

The increasing use of roller bearings on rolling mill machinery gives greater point to shunt or compounded motors in preventing excessive rise in speed when the equipment is running unloaded.

The shunt or compound motor is also easier to control than a series machine and lends itself to dynamic or re-generative braking and Ward Leonard control, whereas a series motor has to be plugged in order to bring it to rest unless a rather complicated form of control is used.

Floating Frame Motors

The motor illustrated in Fig. 17, known as the CMF type, represents a new development intended mainly for direct drives on roller tables. The armature is mounted directly on to the extended shaft of the roller table and the frame is carried on roller bearings at each end of the armature. The frame, instead of being foot mounted in the usual way, is anchored by a toggle device. If, as occasionally happens, the roller table driving shaft is bent through heavy handling, the frame of the motor is able to float about its fixing toggle and still retain the correct air gap relative to the armature.

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